IMPROVING CAPABILITIES FOR DEALING WITH KEY COMPLEXITIES OF WATER AVAILABILITY MODELING

A Thesis

by

HECTOR ELIAS OLMOS ALEJO

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2004

Major Subject: Civil Engineering

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Approved as to style and content by:

Ralph Wurbs (Chair of Committee)	Francisco Olivera (Member)
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ABSTRACT

Improving Capabilities for Dealing With Key Complexities of Water Availability Modeling. (December 2004)

Hector Elias Olmos Alejo, B.S., Universidad Nacional de Colombia

Chair of Advisory Committee: Dr. Ralph Wurbs

Water availability has been of great concern in the State of Texas and many other places worldwide. During 1997-2003, pursuant to the 1997 Senate Bill 1, the Texas Commission on Environmental Quality (TCEQ), its partner agencies, and contractors developed a Water Availability Modeling (WAM) System based on the Water Rights Analysis Package (WRAP) model, developed at Texas A&M University. WAM has been widely applied in the State of Texas and because of its convenience, applications, and capabilities, it is planned to be implemented in other States and Countries.

This thesis addresses different aspects of WAM, including conditional reliability modeling, firm yield analysis following classic and recently developed methodologies, evaluating the impact of different considerations on reliability analyses, simplification of complex WAM datasets and the display of WRAP results into ArcMap.

Conditional reliability modeling evaluates short term diversion/storage reliabilities based on an initial storage level. WRAP-CON has been evaluated and improved, in addition a new modeling methodology has been developed, in which probabilities of occurrence for each hydrologic sequence is based on the relationship between storage and future flows.

Recently developed WRAP capabilities have been evaluated, providing users new tools and increased flexibility. Some of these improvements are firm yield analysis, cycling and dual simulation.

In addition to improved software, guidelines have also been developed, including a set to simplify extremely large WAM datasets, while maintaining the effect of all the other water rights in a basin.

DEDICATION

To my beloved parents, Elías and Elsa

ACKNOWLEDGMENTS

I would like to express my immense gratitude to all those who have helped me to complete my Master's studies and have always supported me, especially Dr. Ralph Wurbs, my professor, advisor and chair of my committee. He always helped me to understand and showed me the path through my entire studies. His help was invaluable. I also would like to thank the Texas Water Resources Institute for funding this project.

I would like to thank all the professors I have had during my graduate studies, they have prepared me for facing a very competitive world. I would also like to thank my colleagues in Water Resources, especially Richard Hoffpauir, Logan Burton and Janghwoan Choi.

I am especially grateful to my parents, thanks to their love, support and encouragement I have reached this goal. Oscar, Laura, Liliana and Adhara thanks for always being there.

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CHAPTER I

INTRODUCTION

Water availability has been of great concern in the State of Texas and many other places worldwide. While in the past it was not possible to quantify the amount of the water resources available, today this is possible, furthermore, it is possible to have an idea of its reliability into the future.

After multiple severe droughts and a growing necessity to expand statewide water availability modeling capabilities, the 1997 Senate Bill 1 directed the Texas Commission on Environmental Quality (TCEQ), its partner agencies, and contractors to develop a Water Availability Modeling (WAM) System. The system was developed between 1997-2003 and is composed of 23 datasets and a simulation model known as the Water Rights Analysis Package (WRAP), developed at Texas A&M University. WAM has been widely applied in the State of Texas and because of its convenience, applications, and capabilities, it is planned to be implemented in other States and Countries.

Due to population growth and increases in water demand, water suppliers are currently conducting planning studies and applying for new water right permits; in some cases, the modeling strategy used to support the application is totally different than the conventional methodologies that have been followed in the past. For instance, the Brazos River Authority (BRA) has recently applied for a system operation permit, which would allow them to operate their reservoirs as a system and therefore increase the permitted diversion amounts significantly. In addition to this permit, the BRA also applied for an interruptible supply of water from the Brazos River. The modeling procedure used to apply for these permits is explained in this document as well as alternative modeling strategies and comparison between results.

This thesis follows the style of the *Journal of the Transportation Research Board*.

Conditional Reliability Modeling (CRM) is also of great importance when doing WAM, since in most cases short term reliabilities are of great importance and the methodology applied by WRAP only estimates long term reliabilities.

It then becomes necessary to have an updated model that can satisfy the current necessities of the water resources community. For some topics, detailed modeling methodologies are described, for others modifications have been done to the current model, while in other cases a new application has been developed.

1.1 OBJECTIVES OF THE RESEARCH

The main research objective involves the evaluation of key complexities in water availability modeling, specific objectives are as follows:

- Develop a set of guidelines to simplify existing WAM datasets
- Perform yield-reliability analysis for alternative system management strategies and modeling premises for the Brazos River Authority System
- Evaluate the impact of the beginning storage adopted for the WRAP simulation on reliabilities and firm yields for reservoirs in the Brazos River Authority System
- Evaluate, improve and describe methodologies to apply the conditional reliability model (WRAPCON)
- Develop a new version of the conditional reliability model, using a different approach than the original WRAPCON and compare results obtained from both models
- Develop a Visual Basic tool to display WRAP results into ArcMap 8x or higher

1.2 ORGANIZATION OF THE THESIS

This thesis is divided into seven chapters and two appendices. The remainder of Chapter 1 briefly describes the Texas water rights system, the WRAP model and the WAM system. Chapter 2 is a review of concepts and published and unpublished work related to the different topics in this thesis. Chapter 3 outlines the methodologies developed to simplify existing WAM datasets. Yield estimates using different modeling strategies are presented in Chapter 4. Conditional reliability modeling following the conditional frequency duration curves, storage-flow frequency and equally likely methodologies is presented in Chapter 5. Chapter 6 describes a tool to display WRAP results in ArcMap 8x. And Chapter 7 provides summary and conclusions of this research.

1.3 TEXAS WATER RIGHTS SYSTEM

Water is classified depending on where it is physically contained; there are four main classes of water: percolating groundwater, where the land owner has no limit on the amount he can withdrawal; underground streams, can be treated as surface streams; diffuse surface water, which does not become property of the state until it reaches a watercourse; and streamflow or surface water. Regarding the use of surface water in the state of Texas, it is required by law to own a water right permit to have the legal right to use it. There are two alternative doctrines to establish the legal right for the use of streamflow, the riparian and the prior appropriation doctrines. The riparian doctrine states that water rights are incidental to the ownership of land adjacent to the stream. The prior appropriation doctrine is based on the concept of “first in time, first in right”. With this doctrine, a water right is not related to the ownership of land, but it is related to a priority established by the dates in which these rights where claimed (*1*). Both doctrines were been used simultaneously in the state of Texas, creating conflict between users; this problem was solved by the Water Rights Adjudication Act of 1967. This act combined both doctrines and adopted the prior appropriation system as the one to be applied in the state of Texas (*2*). After several severe droughts and the problem of having some basins with demands exceeding the amounts of water available, in 1997 Senate Bill 1 directs the Texas Natural Resource Conservation Commission (TNRCC), now known as Texas Commission on Environmental Quality (TCEQ), to develop a water availability model and input databases for the 22 river basins of the state, excluding the Rio Grande, which was completed recently.

The objectives of this water availability model were to provide capabilities for assessing water availability and reliability following the prior appropriation doctrine of the State of Texas; and to develop a computer model for simulating the complexities of surface water management (*3*). The resulting model is the Water Rights Analysis Package (WRAP), developed at Texas A&M University under the direction of Dr. Ralph A. Wurbs.

1.4 THE WATER RIGHTS ANALYSIS PACKAGE (WRAP)

WRAP is documented in detail by its reference/users manuals (*4*); the following is a brief description of the model:

The Water Rights Analysis Package (WRAP) modeling system simulates management of the water resources of a river basin or multiple river basins, under a priority based water allocation system, such as the Texas water rights system. The model facilitates assessment of hydrologic and institutional water availability and reliability for existing and proposed water rights. Impacts due to the development of new projects or management strategies can be evaluated. The model can be applied to any river-reservoir-use system, prior development of the input files (*3*).

WRAP is a component of the Texas Commission on Environmental Quality (TCEQ) Water Availability Modeling (WAM) System. It is composed of three programs:

- WinWRAP is a user interface for applying the programs from a windows environment.
- WRAP-SIM is the river-reservoir water allocation/management system simulation model.
- TABLES is a post-processor that builds specified tables based on the results obtained from WRAP-SIM.
- WRAP-HYD is a utility program for developing inflows and evaporation input files for WRAP-SIM.

WRAP provides great flexibility when simulating different operational policies and water rights scenarios. Water rights may include refilling of storage, instream flow requirements, water diversions, hydroelectric power generation and inflow to the stream. Operating policies may include making water depletions from reservoirs, streams or both, development of multiple-reservoir systems, the use of return flows, interbasin transfers, drought indexes, the definition of water rights target based on current flow or storage conditions and calculation of firm yields. These options are constantly being improved as new requirements from WRAP users emerge.

WRAP uses a monthly time step and assumes a hypothetical repetition of historical hydrology, there is no limit on the number of years that can be simulated. In each sequential month of the hydrologic period of analysis, volume accounting computations are performed for each water right in priority order. The simulation results include sequences of monthly and annual values for all pertinent variables, storage and flow frequency statistics and reliability indices for meeting water-use requirements (*4*).

1.5 EXISTING TCEQ WAM DATASETS

As a result of the Water Availability Modeling project, 21 input data sets (representing all basins in the State of Texas) were developed by different consultants; these data sets are available at the TCEQ website. Each one of them represents the spatial configuration of a basin (set of control points), the water management strategies (water rights) and the river-basin hydrology, represented by naturalized streamflows and reservoir net evaporation-precipitation depths for each month of the hydrologic period of analysis.

There are eight to ten different scenarios for each basin reflecting alternative premises regarding water use, return flows, and reservoir sedimentation. Water use is based on either assuming all permit holders use their full permitted amounts or estimates or water demands based on actual use during recent years. These input data sets will continue to be used in the future by the TCEQ and other entities when investigating different water management strategies. Table 1.1 summarizes the period of analysis, number of primary control points, total number of control points, number of water rights and number of reservoirs for each one of the river basins. For this project, the Brazos River Basin data set for full permitted amounts was used to perform the different analyses.

TABLE 1.1 Summary of Period of Analysis, Number of Control Points, Water Rights and Reservoirs

	River Basins	Period of Analysis	Primary Control Points	Total Control Points	Water Rights	Reservoirs
1	Canadian River Basin	1948-98	12	85	56	47
2	Red River Basin	1948-98	50	443	447	240
3	Sulphur River Basin	1940-96	6	77	82	51
4	Cypress Bayou basin	1948-98	22	158	132	85
5	Rio Grande Basin	1940-00	77	974	2562	90
6	Colorado River Basin and Brazos-Colorado Coastal	1948-98	45	2263	1591	503
7	Brazos River and San Jacinto-Brazos Coastal	1940-97	77	3818	1606	650
8	Trinity River Basin	1940-96	40	1329	1176	702
9	Neches River Basin	1940-96	20	304	327	175
10	Sabine River Basin	1948-98	27	373	308	206
11	Nueces River Basin	1934-96	41	544	376	122
12	Guadalupe and San Antonio River Basins	1934-89	46	1334	853	233
13	Lavaca River Basin	1940-96	7	176	71	22
14	San Jacinto River Basin	1940-96	16	386	164	111
15	Lower Nueces-Rio Grande	1948-98	16	119	70	42
16	Upper Nueces-Rio Grande	1948-98	13	78	35	22
17	San Antonio-Nueces	1948-98	13	49	12	9
18	Lavaca-Guadalupe Coastal	1940-96	1	68	10	0
19	Colorado-Lavaca Coastal	1940-96	2	105	26	10
20	Trinity-San Jacinto Coastal	1940-96	9	83	21	14
21	Neches-Trinity Coastal	1940-96	2	216	134	31

1.6 THE BRAZOS RIVER BASIN AND THE BRA SYSTEM

1.6.1 Basin description

As described in Figure 1.1 the Brazos River Basin extends from eastern New Mexico southeasterly across the state of Texas to the Gulf of Mexico. The overall length of the Brazos River mainstream is greater than 1,100 miles between the New Mexico border and Freeport. The Basin has a length of approximately 640 miles with a width varying from about 70 miles in the High Plains in the upper basin to a maximum of 110 miles in the vicinity of the city of Waco, and then decreases gradually in width to approximately

10 miles near Richmond in the lower basin. It has a drainage area of approximately 45,600 square miles, with about 43,000 square miles in Texas, with the remainder lying in New Mexico (*5*). The basin represents almost 16% of the land area of Texas. About 9,570 square miles in the northwest part of the basin are non-contributing to downstream streamflows. The mean precipitation varies from about 16 in/yr in the western part of the basin to over 50 in/yr in the lowest basin near the Gulf.

FIGURE 1.1 Brazos River Basin.

From its descent from the High Plains and Caprock Escarpment, the Brazos River flows through a semiarid region of gypsum and salt encrusted hills and valleys containing numerous salt springs and seeps. This area of the upper basin is the main source of the salt contamination (*1*).

Land use in the Brazos River Basin is predominantly related to agriculture with 53.8 percent classified as cropland or pastureland and 30.6 percent as rangeland.

Urban land uses comprise only about 0.9 percent of the basin. The main cities in the basin are Lubbock, Waco, Abilene, Bryan-College Station, Kileen and Temple. The population of the Brazos River Basin was in 1980 and 1990 of 1.53 million and 1.73 million respectively (*6*). The population is expected to increase to between 3.1 and 3.8 million people by 2040. Figure 1.2 shows the location of main cities and reservoirs in the Brazos River Basin.

1.6.2 Reservoirs

There are more than 1,200 reservoirs in the Brazos River basin, but only 36 reservoirs have an authorized capacity greater than 10,000 ac-ft. Table 1.2 lists these reservoirs along with its authorized storage capacity and annual diversion amounts. The largest reservoir in the Brazos River Basin is Possum Kingdom reservoir, which is located on the Brazos River in Palo Pinto County. It has an authorized storage capacity of 724,739 ac-ft and an authorized annual diversion of 230,750 ac-ft/yr. It is owned and operated by the Brazos River Authority. The authorized storage capacity of Possum Kingdom represents about 20% of the total combined capacity of all major reservoirs in the Brazos River Basin.

The primary provider of water in the Brazos River Basin is the Brazos River Authority, which holds water rights in nine reservoirs operated by the United States Corps of Engineers USACE (Aquilla, Belton, Georgetown, Granger, Proctor, Somerville, Stillhouse Hollow, Waco and Whitney) and four existing reservoirs that owns and operates (Possum Kingdom, Granbury, Limestone, and Alan Henry). These reservoirs represent about 70% of the conservation storage capacity in the basin. Table 1.3 lists these reservoirs.

The nine previously mentioned reservoirs are operated by the Fort Worth District for flood control, water supply and recreation. Whitney reservoir serves the additional purpose of hydroelectric power generation. The USACE is responsible for flood control operations. Conservation releases are made as directed by the local project sponsor, which for most of the cases is the Brazos River Authority (BRA).

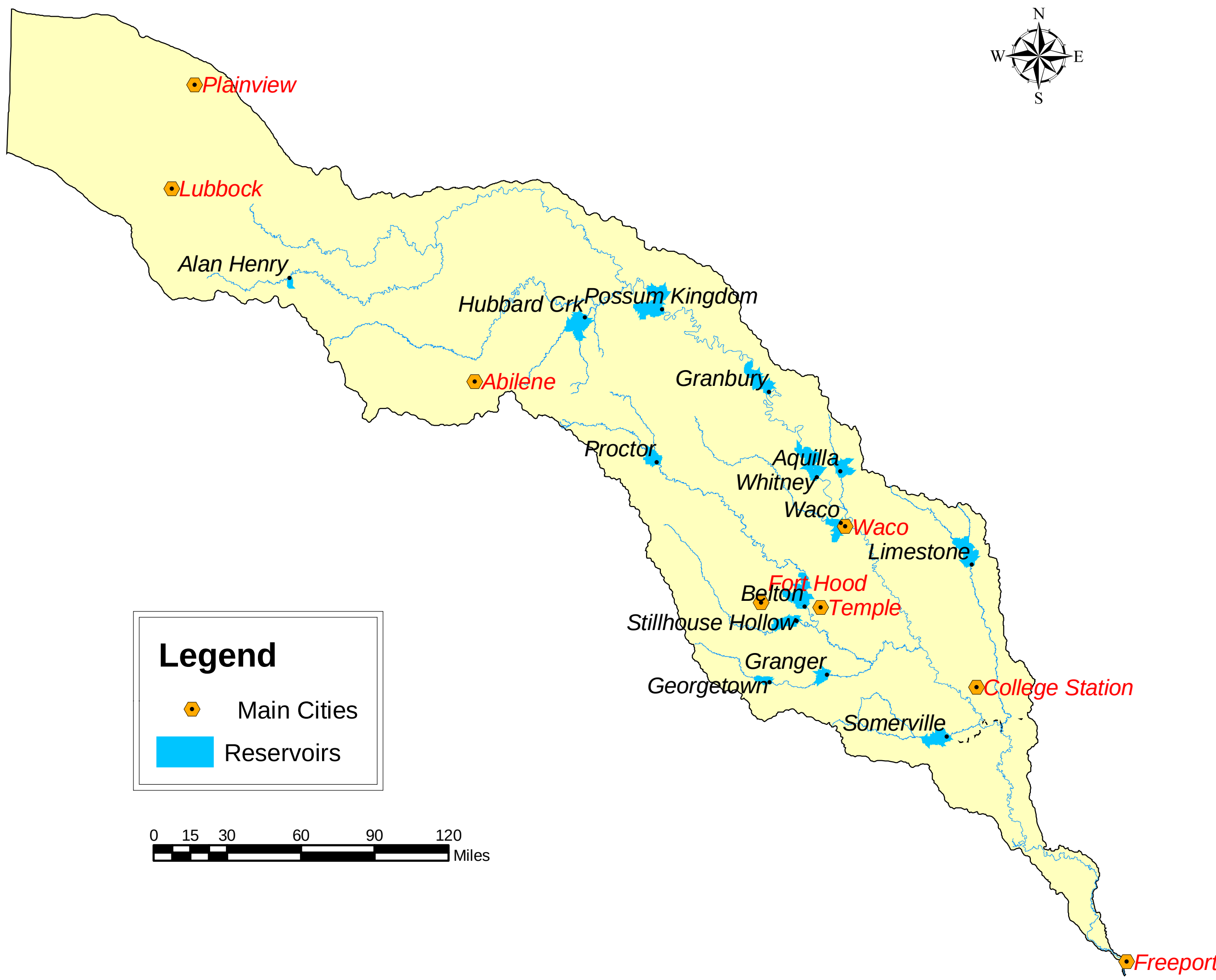


FIGURE 1.2 Main cities and reservoirs in the Brazos River Basin.

TABLE 1.2 Major Reservoirs in the Brazos River Basin and San Jacinto-Brazos Coastal Basin, Source: HDR (7)

Reservoir	Stream	County	Authorized Storage (ac-ft)	Authorized Diversion (ac-ft)	Owner
Abilene	Elm Creek	Taylor	11,868	1,675	City of Abilene
Alan henry	S. Fork Dbl. Mnt. Fork	Garza	115,937	35,000	Brazos River Authority
Alcoa Lake	Sandy Creek	Milam	15,650	14,000	Aluminum Co. of America
Aquilla	Aquilla Creek	Hill	52,400	13,896	U.S. Army Corps of Engineers
Belton	Leon River	Bell	457,600	100,257	U.S. Army Corps of Engineers
Brazoria	Off-Channel	Brazoria	21,700	75,656	Dow Chemical
Bryan Utilities	Unnamed Trib. Brazos River	Brazos	15,227	850	City of Bryan
Cisco	Sandy Creek	Eastland	45,000	2,027	City of Cisco
Cleburne	Nolan Creek	Johnson	25,600	6,000	City of Cleburne
Daniel	Gonzales Creek	Stephens	11,400	2,100	City of Breckenridge
Eagles Nest	Vamers Creek	Brazoria	11,315	1,800	T.L Smith Trust, et al
Fort Phantom Hill	Elm Crek	Jones	73,960	33,190	City of Abilene
Georgetown	North Fork San Gabriel River	Williamson	37,100	13,610	U.S. Army Corps of Engineers
Gibbons Creek	Gibbons Creek	Grimes	32,084	9,740	Texas Municipal Power Agency
Graham/Eddlerman	Flint Creek	Young	52,386	20,000	City of Graham
Granbury	Brazos River	Hood	155,000	64,712	Brazos River Authority
Granger	San Gabriel River	Williamson	65,500	19,840	U.S. Army Corps of Engineers
Harris	Off-Channel	Brazoria	10,200	230,000	Dow Chemical
Hubbard Creek	Hubbard Creek	Stephens	317,750	56,000	West Central Texas MWD
Leon	Leon River	Eastland	28,000	6,301	Eastland Co. WSD
Limestone	Navasota River	Robertson	225,400	65,074	Brazos River Authority
Millers Creek	Millers Creek	Baylor	30,696	5,000	North Central Texas MWD
Palo Pinto	Palo Pinto Creek	Palo Pinto	44,100	13,480	Palo Pinto MWD
Possum Kingdom	Brazos River	Palo Pinto	724,739	230,750	Brazos River Authority
Post	N. Fork Dbl. Mnt. Fork	Garza	57,420	10,600	White River M.W.D
Proctor	Leon River	Comanche	59,400	19,658	U.S. Army Corps of Engineers
Smithers	Smithers Creek	Fort Bend	18,750	34,300	Houston L&P Co
Somerville	Yegua Creek	Washington	160,110	48,000	U.S. Army Corps of Engineers
Sqaw Creek	Sqaw Creek	Somervell	151,500	23,180	Texas Utilities Electric Co
Stamford	Paint Creek	Haskell	60,000	10,000	City of Stamford
Stillhouse Hollow	Lampasas River	Bell	235,700	67,768	U.S. Army Corps of Engineers
Tradinghouse	Tradinghouse Creek	McLennan	37,800	15,000	Texas Utilities Electric Co
Twin Oaks	Duck Creek	Robertson	30,319	13,200	Texas Utilities Electric Co
Waco	Bosque River	McLennan	192,062	79,870	U.S. Army Corps of Engineers
White River	White River	Crosby	44,897	6,000	White River MWD
Whitney	Brazos River	Hill	50,000	18,336	U.S. Army Corps of Engineers
Totals	-	-	3,678,570	1,366,870	-

Wurbs et al. (*1*) provides a detailed description of the Brazos River Basin, the following was extracted from this source:

"*Possum Kingdom reservoir completed in 1941 provides water supply and hydroelectric power. BRA sells the power to the Brazos Electric Power Cooperative. Lake Granbury, completed in 1969, provides cooling water for a gas-fired plant near the Lake and to Squaw Creek reservoir for the Comanche Peak Nuclear Power Plant. Granbury and Possum Kingdom reservoirs provide makeup water, as needed to maintain constant operating levels in Tradinghouse Creek and Lake Creek reservoirs which are owned and operated by utility companies for stream-electric power plant cooling. A desalting water treatment plant provides the capability to treat water from*

TABLE 1.3 Reservoirs Operated by the U.S Army Corps of Engineers (USACE) and the Brazos River Authority

Reservoir	County	Owner	Year completed	Conservation storage (Ac-Ft)	Permitted Diversion (Ac-Ft/yr)
Alan Henry	Garza and Kent	Lubbock & BRA	1992	115,937	35,000
Possum kingdom	Palo Pinto	BRA	1941	724,739	230,750
Granbury	Hood	BRA	1969	155,000	64,712
Whitney	Hill and Bosque	USACE	1951	50,000	18,336
Aquila	Hill	USACE	1983	52,400	13,896
Belton	Bell	USACE	1954	457,600	112,257
Stillhouse Hollow	Bell	USACE	1968	235,700	67,768
Georgetown	Williamson	USACE	1980	37,100	13,610
Granger	Williamson	USACE	1980	65,500	19,840
Somerville	Burleson and Washington	USACE	1967	160,110	48,000
Limestone	Leon, Limestone and Robertson	BRA	1970	225,400	65,074
Proctor	Comanche	USACE	1963	59,400	19,658
Waco	McLennan	USACE	1965	192,062	79,870
Allens Creek	Austin	BRA, Houston and TWDB	Not constructed	145,533	99,650

Lake Granbury to supplement the water supply for the City of Granbury. Lake Limestone, completed in 1978, supplies water to off-channel cooling Lakes owned by the Texas Power and Light Company. BRA uses Lake Belton to supply water under contracts with the Cities of Temple and McGregor, and through Bell County Water Control and Improvement District No 1 and two water supply corporations, to several other cities and communities. Water from Lake Whitney is contracted for use by the Cities of Cleburne, Whitney and Rio Vista."

"*Lake Waco supplies the City of Waco. Water from Proctor reservoir is provided to several cities under a contract between BRA and the Upper Leon River Municipal Water District. Proctor also provides water for agricultural use to individual farmers around the Lake and to a corporation of farmers along the Leon River downstream of the dam. Stillhouse Hollow reservoir supplies water to a number of communities and rural water supply corporations. Somerville reservoir and Georgetown, Granger and Aquilla reservoirs are also committed for municipal and industrial water supply*."

In addition to the uses cited above, the BRA system delivers water to customers in the lower basin, such as large chemical plants, thermal-electric generating plants, municipalities, industries and rice farmers.

CHAPTER II

LITERATURE REVIEW

2.1 DEFINITION OF TERMS

Reliability: Is the probability of being in a non-failure state during any particular time period. Failure may relate to the imposition of restrictions of a specified magnitude or reaching the dead storage level in one or more reservoirs (*8*). According to Wurbs and Bergman (*9*) reliability estimates can be formulated in terms of periods and volume. Period reliability refers to the proportion of time that the system is able to meet demands, while volume reliability defines the ratio of the volume delivered to the volume demanded.

Yield: There are multiple definitions of yield Dandy et al. (*8*) define yield as the quantity of water that can be supplied in each time step at a specified reliability. Yield can also be defined in hydroelectric energy instead of water terms (*10*). Wurbs and Bergman (*9*) define yield as the estimated maximum release or withdrawal rate which can be maintained continuously during a repetition of the hydrologic period of record. Firm yield is the yield that has 100% reliability.

Reliability curve: A reliability curve establishes a relation between a diversion/storage amount and its probability of being equaled or exceeded. The area under the curve corresponds to the expected value of the variable (*11*).

Conditional probability: Is the probability of occurrence of an event A given the fact that event B (condition) occurred. (*11*).

2.2 SIMPLIFICATION OF WATER RIGHTS DATASETS

Since water availability modeling requires voluminous input data, such as streamflow data at each location, previous studies tend to simplify the study area by aggregating all the water rights in the basin to selected control point locations near streamflow gages, where flow data was available (*1*). This practice generated a simple dataset, but the dataset was not flexible to analyze rights that may have been located far away from the gage.

2.3 YIELD ANALYSIS

Multiple studies have been done in the past in order to have an understanding of the amount of water that can be provided under certain conditions. Determining yields is a key element in almost all studies and decisions involving water or water based supplies such as energy.

There are different methods to determine yields in a system (1) storage probability theory; (2) mathematical programming or optimization techniques; (3) simulation of a stream/reservoir system for a specified hydrologic sequence.

Probability theory is based purely on stochastic properties of flows and therefore storage. The objective of stochastic storage analysis is to determine the probability distribution of reservoir storage. McMahon and Mein (*12*) describe the probability matrix methods, and Klemes (*13*) describes the application of stochastic theory of reservoir storage.

Optimization or mathematical techniques have been applied in multiple studies. The objective of an optimization model is to find a set of decision variables that maximize or minimize an objective function subject to different constraints. There are fully optimization models and simplified optimization models; both have perfect knowledge of future inflows. The full optimization model requires constraints for each year and month of the simulation, while the simplified optimization model only requires constraints for each year and only 12 monthly constraints per reservoir. Size is the main limitation of the optimization model, when long time periods are considered; In general, the longer the period of simulation, the more representative the results are, so when having long periods of record, the simplified optimization model may be more adequate to be used, although the result would be only an approximation to the full optimization result. Dahe and Srivastava (*14*) describe the use of the yield model which is a simplified optimization model to optimize a multi-reservoir multi-yield system with allowable deficit in annual yield.

Simulation models are the most commonly tool used today for analyzing a reservoir system yield, with many authorities using custom-built computer models of their system to assess its yield as well as to assist in operations and managing. There are multiple generic computer models available, the most commonly known are HEC-3 and HEC-5 (*15*), recently replaced by ResSim (*16*), MODSIM (*17*), MIKEBASIN (*18*), RIVERWARE (*19*), MITSIM (*20*), RESQ (*21*), IRAS (*22*), ACTEW (*23*) and WRAP (*4*) among others. A simulation model can accurately evaluate the system yield for an assumed set of operating rules, but cannot find the maximum yield that can be achieved by adopting the best set of operating rules, these rules can only be found by trial and error or by optimization. Contrary to an optimization model, a simulation model can use actual operating rules and these rules are independent of past and future inflows; there is no complete knowledge of future inflows and the simulation model only supplies a specified volume for each time step, depending on the operating rules adopted. Although simulation models do not allow establishing the maximum yield or optimal operating rules directly, they allow evaluating the system behavior when modifying different factors.

Wurbs and Bergman (*9*) analyze the impact of different factors on a reservoir yield; these factors were categorized as (1) Basin Hydrology; (2) Basin wide water management and (3) Reservoir system simulation. Basin hydrology involved modifications to streamflow data, evaporation data and channel losses. Basin wide water management refers to basin changes (land use, water use, river regulations, changes in base flow among others). Reservoir system simulation refers to system operating policies, multiple purpose operations, seasonal distribution of water use, reservoir sedimentation and definition of water supply storage failure. It was found that estimates of yield versus reliability relationships and firm yield depend greatly on how the above mentioned factors were defined when simulating the system.

Another optimization procedure is network linear programming; models of this type are SIMYLD-II (*24*), WATHNET (*25*), DWRSIM (*26*). WATHNET performs a multiple-period simulation of a system while using network linear programming to optimize operations at each time step. As simulation models, this model does not anticipate future inflows into the system. In order to identify the firm yield, an iterative process is performed by the user, the yield is entered as a demand, and if no shortages occur then the target is increased until the system does not fully meet the demand (*8*).

A comparison between the different modeling techniques available is documented by (*8*) they concluded that fully optimization models give the maximum possible yield, but may be difficult to apply them on long term simulations; simplified optimization models give a result greatly dependant on the assumptions used to evaluate the critical period, but are more convenient when simulating long periods of record; simulation models give a yield estimate dependant on the accuracy of the operating policies utilized; WATHNET gives a value between the fully optimization and the simulation techniques and may be the best way to analyze a system based on yield estimation results and system performance.

2.4 EFFECT OF INITIAL STORAGE ON THE CAPACITY-RISK-YIELD CURVE OF A RESERVOIR

Duranyildiz (*27*) evaluated the effect of the initial storage on the capacity-risk-yield relationship on a reservoir. By using stochastic theory, 1000 synthetic flow series were generated and analyzed for different operating periods. Initial storages were assumed to be full or half full, additionally randomly selected initial storages were analyzed. He concluded that the effect of the initial storage decreases with the increasing risk; and the assumption made for the initial storage has a considerable effect on the required reservoir capacity, especially for small values of the standard net mean input and the risk.

In order to remove the influence of initial conditions on behavior analysis storage estimates, the inflow sequence used is often concatenated with itself, with the resulting concatenated sequence being routed through the reservoir simulation beginning with the reservoir full. In this way, two complete cycles of the inflow sequence are consecutively routed through the system, with the reliability being estimated only for the second cycle (*28*).

2.5 RIVER-RESERVOIR MODELS

2.5.1 HEC-RESSIM

HEC-RESSIM is a computer program developed by the US Army Corps of Engineers Hydrologic Engineering Center (*16*), comprised of a graphical user interface (GUI) and a computational program to simulate reservoir operations. It replaced the old HEC-5 and was developed to assist in planning studies, evaluate proposed reservoirs in a system and to assist in sizing the flood control and conservation pools. The program is useful in selecting the proper reservoir releases during flood emergencies in order to minimize flood damages, while maintaining a balance of flood control storage among the reservoirs.

2.5.2 MODSIM

The MODSIM model was developed by Colorado State University, and it is used to simulate a priority based system. The program is split into two functional pieces, a graphical user interface to ease river network creation, and a state of the art water rights network solver, where a river basin is represented by nodes and links, where nodes symbolize points of inflow, diversion, confluence or storage; and links represent river reaches, channels or pipes. The use of network flow optimization actually serves to enhance the ability to simulate complex river basin systems. MODSIM was originally an extension of the SIMYLD network simulation model from the Texas Water Development Board; MODSIM simulates several types of water rights, including direct flow rights, instream flow rights, reservoir storage rights and reservoir system operations. The model is fully documented in Labadie (*17*) A recent version of the model includes surface water and aquifers; with a graphical user interface (GUI) allowing users to create any river basin system topology by simply clicking on various icons and placing system objects in any desired configuration on the display. MODSIM has the ability of using a monthly, weekly or daily time steps, based on developing the appropriate input data.

2.5.3 MIKEBASIN

MIKEBASIN is a commercial software package, developed by the Danish Hydraulic Institute (DHI), it is integrated with ArcView3.2 GIS to provide additional analysis tools. It also interacts with Microsoft Excel to facilitate visualization of results and organizing data. The program is a network flow model with links and nodes, where links represent individual stream sections and the nodes represent confluences, diversions, reservoirs, or water users. The package incorporates a deterministic, conceptual rainfall-runoff model for rural catchments; based on data such as precipitation and potential evapotranspiration combined with surface and groundwater storage, the model computes runoff. The water balance in the model interacts between the demands and inflows to the basin from surface water and groundwater. The model also considers water quality and pollutant loads. The water quality solution assumes purely advective transport; decay during transport can be modeled. The groundwater description uses the linear reservoir equation (*18*). License cost is $3,000 dollars per class set, and $300 dollars to update each set.

2.5.4 RIVERWARE

RIVERWARE is a generalized model developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADWES) at the University of Colorado. It was developed in collaboration with the Tennessee Valley Authority and the U.S. Bureau of Reclamation. This model is an object oriented program, with a user friendly interface that allows to easily define a system and assign properties to different objects. Objects include storage reservoirs, reaches, diversions, gages and others. Each object has its own processes that are modeled, for example a reservoir object performs mass balances, evaporation computations, bank storage, spills and water quality analysis. The model offers three different main simulation options: Pure simulation, driven by user inputs; rule-based simulation, driven by if-then-else operating policies input by the user; and linear pre-emptive goal programming optimization. All these options have allowed different river authorities to replace their old site specific models with RIVERWARE and type their operating rules and constraints just as an input to the model, instead of having to change the computer code to meet their objectives.

Variable time step is another advantage in RIVERWARE, the model can be applied from an hourly to a monthly time step, allowing it to be used for operating and long term planning purposes as well. Features, detailed characteristics and applications of the program were reported by Zagona et al. (*19*). License cost is around $6,500 dollars for the first year and an annual renewal of $2,500 dollars.

2.5.5 IRAS

The IRAS model was developed as a tool for supporting the management and planning of water resources systems. The model allows the joint simulation for each time period of surface and groundwater flows, storage volumes of water, loads and concentrations of pollutants and hydropower. The river system is represented by a network of nodes and links, with the nodes representing aquifers, gauges, consumption sites, Lakes, reservoirs, wetlands, confluences, and diversions. Links are river reaches or water transfers to the nodes. The IRAS model simulation is based on water quality balance and decrease of pollutant loads by the chemical or biological reactions and the floods propagation. The model time step is defined by the user and varies from some hours to a month. The model allows to define operational rules for the reservoirs and to treat diversions under a priority basis. The output of the model includes a system performance in meeting demand requirements; flows, storage volumes, energy, and water quality throughout system (*29*).

2.5.6 AQUARIUS

AQUARIUS is a computer model depicting the temporal and spatial allocation of water flows among competing traditional and nontraditional water uses in a river basin. The water allocation is driven by economic principles and optimizes a nonlinear system, where supplies and requested demands are prescribed on the system. Water resource systems are described in a node-link architecture, with river reaches, reservoirs, Lakes, and demand objects describing the system. A drag and drop user interface helps define the system layout, which is then translated into a quadratic objective function with linear constraints (*18*).

2.6 CONDITIONAL RELIABILITY

2.6.1 Concepts

The first author that addressed the prediction of the probability distribution of storage at the end of a period of analysis given an initial condition was Moran *(30)*. The methodology used a known initial storage to determine the expected probability distribution of storage at the end of one year. It was assumed that the inflow distribution was known, that annual inflows were independent, and that inflows occurred during wet months and outflows during dry months. The methodology lacked the possibility of modeling water rights and calculate their reliabilities.

Gould (31) improved Moran's model, accounting for seasonality and serial correlation of inflows by computing a correlation matrix by applying a simulation analysis using historical data on monthly inflows, net evaporation and storage variation. This simulation was based on conservation of mass, a given assumed initial storage and monthly demands with historical inflows and net evaporation sequences. In this methodology, the average fluctuations in storage are simulated by a Markov chain, which translates into a transitional matrix **T**. The reservoir storage is divided into **K** levels, so **T** that contains **K**^{2} elements representing the probability of ending a year in each particular storage level, considering each possible starting level for that year.

$$T = \begin{matrix} t_{11} & t_{12} & \cdots & t_{1K} \\ t_{21} & \vdots & & \vdots \\ \vdots & \vdots & t_{ij} & \vdots \\ t_{K1} & \cdots & \cdots & t_{KK} \end{matrix} \tag{2.1}$$

The probability distribution one year ahead is computed by

$$P_{t+1} = T \cdot P_t \tag{2.2}$$

Where P_t and P_{t+1} are vectors representing the probability distribution of storage in years t and t+1, respectively. P_j represents the probability of being in the j^{th} reservoir level.

After repetitive application of this process to project the probability distribution of storage one year into the future, a steady state is achieved and the probability distribution becomes independent of the initial storage condition.

Vaugh and Maidment (*32*) developed the transient analysis methodology, this model uses a monthly reservoir contents simulation and historical sequences of monthly inflows and net evaporation.

Each simulation starts with a fixed initial storage condition in each reservoir and routs historical sequences of inflows and net evaporation through the system following system operation rules and monthly distributions of demands. Applying the mass balance equation, the end of period storage is found for each month, until the simulation length is reached. The storage levels for each reservoir at the end of the simulation are stored and a new simulation starting with the same initial storage condition is performed using the next sequence of hydrologic data. Reliabilities are computed by building a frequency table of the recorded percentages of target met from the various simulations. This procedure assumes that each sequence of the historic hydrologic data is equally likely to occur during the period of analysis.

2.6.2 Conditional reliability models

Many of the reported river-reservoir models could be used to apply a conditional reliability analysis, by setting manually the initial conditions and organizing the hydrologic data to reflect only portions of the historical record.

HYDROSIM

HYDROSIM was developed by the Tennessee Valley Authority in the 1980's to model their 42 reservoir system in the Tennessee Valley Region, it is thoroughly described in (*33,34*). The objectives of this system are to regulate the streamflow primarily for promoting navigation and controlling floods, in addition the system is operated as part of a large hydrothermal power system, where all reservoirs are equipped with hydro power generation facilities.

The TVA had a need of a computer model to simulate their system in order to have a more efficient use of historical data, evaluate new operating requirements, improve long range guidance and integrate weather forecasts among others. The model was developed to model long term, week to week variations in water level, discharge and electrical generation for all 42 reservoirs.

By using HYDROSIM, it was possible to obtain the most optimum weekly operational schedule to satisfy prespecified objectives following a priority order. The modeling procedure starts by defining the initial reservoirs storage. For the first week, the local streamflow forecast is used to schedule the system by applying a highly efficient linear programming algorithm to satisfy the objectives in a priority order. Since weather in the Tennessee Valley is highly unpredictable, where extreme events can occur in a period as short as 2 weeks, beyond the first week, it is assumed that any of the historical weekly flows recorded since 1903 can recur. The user can specify any of the sequences in the hydrologic record and the system is simulated from 1 to 52 weeks.

After the model has been run, a complete system schedule is available and results including end of week headwater elevations, average weekly releases and average weekly hydro generation for each reservoir are saved. The model includes graphic capabilities which in coordination with output analysis programs display important information to reservoir managers.

According to (*19*), this model has been replaced by RIVERWARE which is a generalized model rather than site specific, and provides more flexibility and capabilities than HYDROSIM.

PROSTOR

As a result of Vaugh's and Maidment's (*32*) work, a model called PROSTOR (PROject STOrage) was created. This model was developed exclusively for the Highland Lakes in Central Texas. The model is capable of apply either the Gould's model or the transient analysis model, and calculate the probability distribution of future reservoir storage level several years into the future

CHAPTER III

GUIDELINES TO SIMPLIFY AN EXISTING WAM DATASET

Some of the Water Availability Modeling datasets are extremely large and complex, which translates into practical difficulties when dealing with many applications. As an example, the Brazos River Basin TCEQ WAM dataset has 3811 control points, 1810 water rights, and 695 reservoirs. Working with a dataset as voluminous as this one is not practical in cases such as: when trying to understand its behavior, updating the dataset with new information, experimenting new operating strategies and trying to track computational procedures.

In order to facilitate these tasks, a methodology has been developed to reduce WAM datasets to simpler datasets still taking into account the effect of the many other reservoirs and water users in the basin. The key point in this methodology is to be able to define which flows belong to the control points of interest.

All unappropriated flows and streamflow depletions made during the complete dataset simulation are extracted for each one of the control points of interest. Streamflow depletions represent all the water that was depleted by each water right to meet its demand or refill storage; unappropriated flows represent water that remained available at the control point, after all the water rights have made their depletions, therefore it is water available to new water rights. After manipulating these two types of flows, a new set of “naturalized” flows is developed, these “naturalized” flows represent all the water available to the control points of interest.

Theoretically the results obtained from the original and the simplified dataset should be identical. This technique will be applied numerous times in this document. All the concepts and procedures required to create a simplified WAM dataset are described in the following sections.

3.1 ORIGINAL DATASET SIMULATION

A simulation using the original WAM dataset has to be run as a first step. From now and on, this simulation will be referred to as “Full simulation”. Prior to performing the full simulation, all return flows should occur on the next month. This is to ensure that all the return flows are available at the beginning of the priority loop on each month and avoid during the simplified dataset simulation, senior rights taking any additional water (water that junior rights got access to thanks to returning flows that were available during the priority loop).

3.2 SELECTION OF CONTROL POINTS AND RESERVOIRS

Defining which control points and reservoirs are going to be included in the simplified dataset, is a very important step. Control points that contribute to build a well defined network should be included, although it is also possible to develop single control point simplified datasets.

In the case of the Brazos River Basin, the simplified dataset includes the 14 major reservoirs in the basin and additional control points of interest, such as gaging stations at confluence points or locations of interest.

A list of the reservoirs and gaging stations included in the simplified dataset for the Brazos River Basin is shown in Tables 3.1 and 3.2.

A map showing the gaging stations and reservoirs included in this simplified dataset is shown in Figure 3.1. The control points included in the simplified dataset are shown in Figure 3.2; these are the actual names of each control point within the dataset.

TABLE 3.1 Reservoirs Included in the Brazos River Basin Simplified Dataset.

BWAM_ID	RESERVOIR ID	Name
4146P1	ALANHN	Lake Alan Henry
421331	HUBBRD	Hubbard Crk Lake
515531	POSDOM	Possum Kingdom Lake
515631	GRNBRY	Lake Granbury
515731	WHITNY	Lake Whitney
515831	AQUILA	Lake Aquilla
509431	LKWACO	Lake Waco
515931	PRCTOR	Lake Proctor
516031	BELTON	Lake Belton
516131	STLHSE	Lake Stillhouse Hollow
516231	GRGTWN	Lake Georgetown
516331	GRNGER	Lake Granger
516431	SMRVLE	Lake Somerville
516531	LMSTNE	Lake Limestone

TABLE 3.2 Gaging Stations Included in the Brazos River Basin Simplified Dataset.

BWAM_ID	Stream	Near_City	USGS_code
DMAS09	Double Mountain fork	Aspermon	USGS08080500
BRSE11	Brazos	Seymour	USGS08082500
BRSB23	Brazos	South Bend	USGS08088000
BRDE29	Brazos	Dennis	USGS08090800
BRWA41	Brazos	Waco	USGS08096500
LEHM46	Leon	Hamilton	USGS08100000
LEGT47	Leon	Gatesville	USGS08100500
LRCA58	Little	Cameron	USGS08106500
BRBR59	Brazos	Bryan	USGS08109000
NABR67	Navasota	Bryan	USGS08111000
BRHE68	Brazos	Hempstead	USGS08111500
BRRI70	Brazos	Richmond	USGS08114000

3.3 SELECTION OF WATER RIGHTS

A list of all the water rights and instream flow requirements that take their water from any of the control points or reservoirs included in the simplified dataset, should be developed. Some restrictions that apply are described in the next section.

In the case of the Brazos River Basin, a total of 130 water rights and instream flow requirements are included in the simplified dataset.

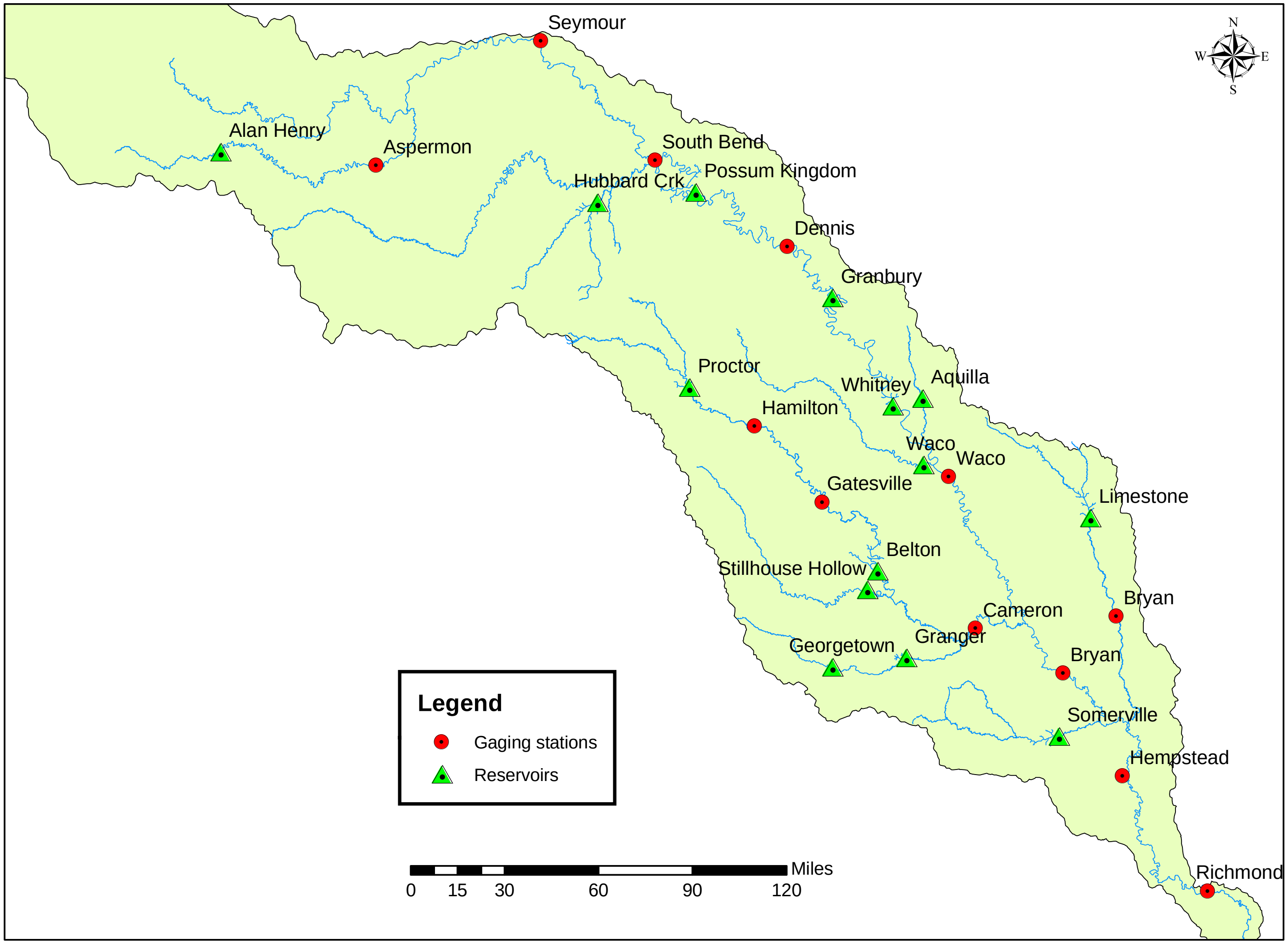
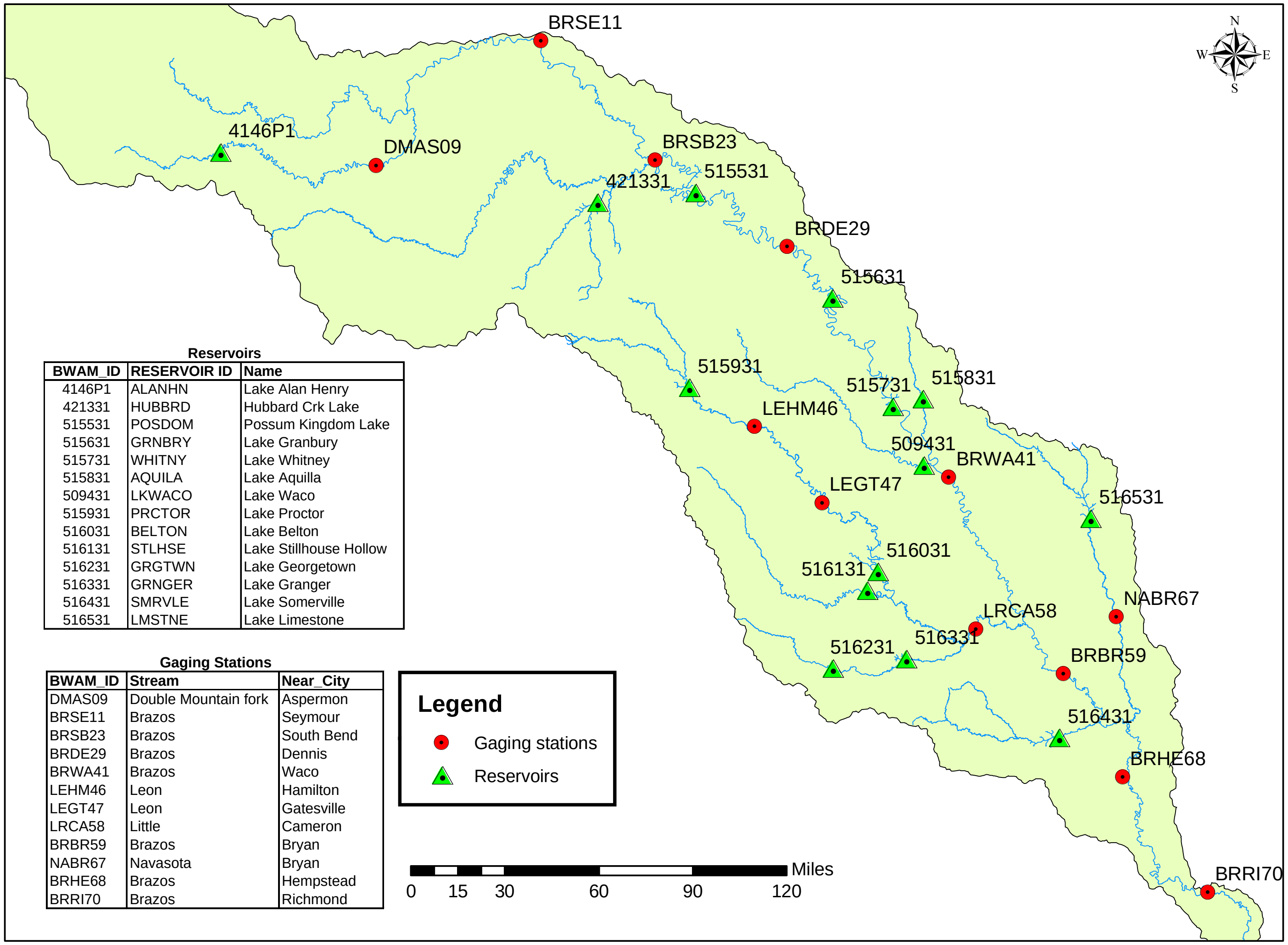


FIGURE 3.1 Location of all reservoirs and gaging stations Included in the Brazos River Basin Simplified Dataset



Reservoirs

BWAM_ID	RESERVOIR ID	Name
4146P1	ALANHN	Lake Alan Henry
421331	HUBBRD	Hubbard Crk Lake
515531	POSDOM	Possum Kingdom Lake
515631	GRNBRY	Lake Granbury
515731	WHITNY	Lake Whitney
515831	AQUILA	Lake Aquilla
509431	LKWACO	Lake Waco
515931	PRCTOR	Lake Proctor
516031	BELTON	Lake Belton
516131	STLHSE	Lake Stillhouse Hollow
516231	GRGTWN	Lake Georgetown
516331	GRNGER	Lake Granger
516431	SMRVLE	Lake Somerville
516531	LMSTNE	Lake Limestone

Gaging Stations

BWAM_ID	Stream	Near_City
DMAS09	Double Mountain fork	Aspermon
BRSE11	Brazos	Seymour
BRSB23	Brazos	South Bend
BRDE29	Brazos	Dennis
BRWA41	Brazos	Waco
LEHM46	Leon	Hamilton
LEGT47	Leon	Gatesville
LRCA58	Little	Cameron
BRBR59	Brazos	Bryan
NABR67	Navasota	Bryan
BRHE68	Brazos	Hempstead
BRRI70	Brazos	Richmond

FIGURE 3.2 Location of all control points Included in the Brazos River Basin Simplified Dataset

3.4 INSTREAM FLOW REQUIREMENT EXCEPTION

Instream flow requirements that do not use reservoir storage should not be included in the simplified dataset, since their effect is reflected on the amount of water that was diverted by every water right during the full simulation. Instream flow requirements that make use of reservoir storage should be included in the simplified dataset. Since this type of Instream flow requirement uses reservoir releases during the full simulation, reservoir storage level decrease to later be refilled by performing a streamflow depletion. This streamflow depletion is included in the new “naturalized flows”, therefore the instream flow requirement record that uses reservoir storage should be included in the simplified dataset, with one modification: the instream flow record should be replaced with a type 3 water right (no streamflow depletions) with the target set as a Target Series (TS) equal to the reservoir releases made during the full simulation.

An example in the Brazos River basin better illustrates this concept. The control point at Lake Aquilla has one instream flow requirement that uses reservoir storage (IFC5158_1).

```
 2     8      16              32  36  40                       64
-----------------------------------------------------------------------
IF515831    362.   UNIFO19761025   2   4              IFC5158_1
WSAQUILA  52400.                               0
OR515831                                  -1
```

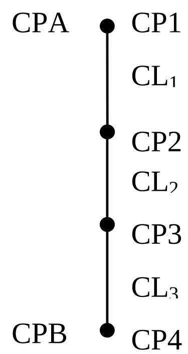
This instream flow requirement is modified as shown below.

```
 2     8    16              32  36  40      64                      80
-----------------------------------------------------------------------
WR515831             19761025   3   2  0.0000                IFC5158_1
TS        1940    30.7      0.0    30.7      0.0     0.0     0.0     0.0
TS        1941     0.0      0.0     0.0      0.0     0.0     0.0     0.0
….
TS        1997     0.0      0.0     0.0      0.0     0.0     0.0     0.0
WSAQUILA  52400.                             0
OR515831                                -1
```

3.5 CHANNEL LOSS FACTORS FOR THE SIMPLIFIED DATASET

Channel loss factors have to be calculated for the new reaches. These new reaches originally were composed of several small reaches, each one of them with a channel loss factor. The new channel loss factor should reflect the effect of the original reaches, so they should be lumped together.

After extracting all the channel loss factors corresponding to intermediate control points, the channel loss coefficient for the new reach is calculated as $CL = 1 - [(1 - CL_1)(1 - CL_2)(1 - CL_3)]$ in the case of 3 reaches being reduced to one reach.



$$CL_{A-B} = 1 - [(1 - CL_1)(1 - CL_2)(1 - CL_3)]$$

FIGURE 3.3 Schematic of a 3 reaches system converted to a single reach system.

TABLE 3.3 Channel Loss Factors for the Reach Between 4146P1 and DMAS09

CP	CLF
4146P1	0.0360
W12411	0.0000
CON244	0.1700
371701	0.0310
371801	0.0310
371802	0.0050
371803	0.0310
371901	0.0500
CON009	0.1610
372201	0.0000
372202	0.0100
372203	0.0260

In the case of the Brazos River Basin, for the reach between 4146P1 (Lake Alan Henry) and DMAS09 (gage at Aspermon), the channel loss factor (CLF) values for the reaches that exist in the complete WAM dataset are shown in Table 3.3.

The channel loss factor for the new reach between Lake Alan Henry and the gage at Aspermon is 0.4433.

3.6 SIMPLIFIED .DAT FILE

The simplified dataset input files use the same format as any dataset that is intended to be run using WRAP. It is composed of .DAT, .INF and .EVA files, no .DIS file is necessary since all flow distributions have been already done in the full simulation. As a consequence of this, if any evaporation-precipitation adjustments were performed during the full simulation, it is no longer necessary to apply those in the simplified dataset, since the new evaporation depths already reflect those adjustments.

Information for control points should only be included for those control points included in the simplified dataset. It is recommended to draw a schematic of the simplified dataset and use it to define the control point information.

The inflows at every control point are included within the .INF file and are already distributed. The evaporation-precipitation information is also read from the .EVA file. The channel loss factor calculated on section 3.4 should be included on the control point information. For the Brazos River Basin simplified dataset, the control point information looks as shown in Figure 3.4.

If constant inflows or outflows (CI records) are used in the complete dataset, none should be included on the simplified dataset.

All the water right records included in the list developed on section 3.2 should be included in the new DAT file. The only modifications that should be done are those indicated in section 3.3 (regarding IF records). No return flows should be done, since during the full simulation all return flows were delivered the following month, added to the naturalized flows and later depleted by the water rights following the priority order. Therefore these return flows are already reflected on the new “naturalized flows”, if return flows are allowed on the simplified dataset, return flows would be double counted.

```
** CP RECORDS
**      2         3        4        5        6        7        8        9       10
**CPID       D/S CPDT(1) CPDT(2) INMETHOD    CPIN                     EWA       CL
CPDMJU08  4146P1                            1               NONE       -3   0.0793
CP4146P1  DMAS09                            1                          -3   0.4433
CPDMAS09  BRSE11                            1               NONE       -3   0.4918
CPBRSE11  BRSB23                            1               NONE       -3   0.4205
CPHCAL19  421331                            1               NONE       -3   0.1287
CPBSBR20  421331                            1               NONE       -3   0.0893
CP421331  BRSB23                            1                          -3   0.2352
CPBRSB23  515531                            1               NONE       -3   0.0179
CP515531  BRDE29                            1                          -3   0.0241
CPBRDE29  515631                            1               NONE       -3   0.0119
CP515631  515731                            1                          -3   0.0267
CP515731  BRWA41                            1                          -3   0.0090
CP515831  BRWA41                            1                          -3   0.0090
CPNBCL36  509431                            1               NONE       -3   0.1604
CP509431  BRWA41                            1                          -3   0.0218
CPBRWA41  BRBR59                            1               NONE       -3   0.0237
CPLEDL43  515931                            1               NONE       -3   0.1767
CPSADL44  515931                            1               NONE       -3   0.1520
CP515931  LEHM46                            1                          -3   0.3795
CPLEHM46  LEGT47                            1               NONE       -3   0.0119
CPLEGT47  293631                            1               NONE       -3   0.0257
CP293631  516031                            1                          -3   0.0000
CP516031  LRCA58                            1                          -3   0.0276
CPLAYO51  516131                            1               NONE       -3   0.0070
CP516131  LRCA58                            1                          -3   0.0257
CP516231  516331                            1                          -3   0.0080
CP516331  LRCA58                            1                          -3   0.0149
CPLRCA58  BRBR59                            1               NONE       -3   0.0364
CPBRBR59  BRHE68                            1               NONE       -3   0.0247
CPNAGR64  516531                            1               NONE       -3   0.0090
CPBGFR65  516531                            1               NONE       -3   0.0020
CP516531  NAEA66                            1                          -3   0.0050
CPNAEA66  NABR67                            1               NONE       -3   0.0100
CPNABR67  BRHE68                            1               NONE       -3   0.0383
CPEYDB61  516431                            1               NONE       -3   0.0169
CPMYDB60  516431                            1               NONE       -3   0.0199
CP516431  BRHE68                            1                          -3   0.0238
CPBRHE68  BRRI70                            1               NONE       -3   0.0236
CPBRRI70     OUT                            1               NONE       -3   0.0257
```

FIGURE 3.4 Control point information for the Brazos River simplified dataset.

3.7 EVAPORATION-PRECIPITATION DEPTHS

Since some datasets perform evaporation-precipitation adjustments, the original evaporation-precipitation depths would no longer work with a simplified dataset. Fortunately, the actual evaporation-precipitation depths used within the calculations are included in the reservoir output file, so these are the evaporation depths that are going to be used within the simplified dataset.

In order to build the new .EVA file, a new record in TABLES was created. A 3EPD record will output the evaporation-precipitation depths for every control point. It is recommended to group the output by year, following this format:

3EPD   EV   1

Since this record outputs the net evaporation-precipitation depths associated with each reservoir, it is necessary to change the ID to the one of the corresponding control point.

3.8 “NATURALIZED” FLOWS

This is probably the key concept when simplifying a dataset. Streamflow depletions and unappropriated flows at each control point, represent the amount of water depleted from the stream to refill storage or meet demands, and available flows remaining on the stream after all water rights have made their depletions, respectively.

The simplified dataset is based on working only with water that was taken by selected water rights during the full simulation, therefore only streamflow depletions made by those rights and unappropriated flows are considered. A methodology applied in WRAP to develop naturalized flows from gaged streamflows and known water depletions is applied. This methodology adjusts all gaged streamflows, by adding known streamflow depletions and applying these adjustments to all downstream locations. In this particular case, unappropriated flows represent gaged streamflows, and streamflow depletions represent the known water depletions.

Assume a system with 3 control points and two water rights, one at CP1 and another one at CP2. After performing the complete simulation, these are the values for unappropriated flows and streamflow depletions, see Table 3.4.

TABLE 3.4 Unappropriated Flows and Streamflow Depletions Example

CP	UNA	DEP
1	1000	100
2	1000	200
3	1000	0

The reach below CP1 has a channel loss factor of 0.1, as well as the reach below CP2. The system is shown in Figure 3.5. The new inflow value at CP1 should be the sum of unappropriated flows plus streamflow depletions:

$$1000+100 = 1100$$

For CP2, the new inflow should be the sum of unappropriated flows at CP2 plus streamflow depletions at CP2 plus the fraction of the streamflow depletions made at CP1 that would have reached CP2:

$$1000+200+100*(1-0.1)=1290$$

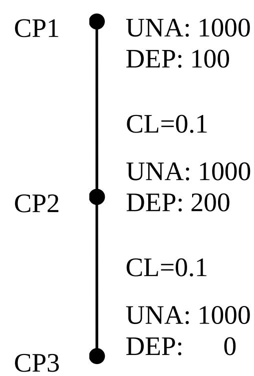


FIGURE 3.5 Unappropriated flows and streamflow depletions example.

Similarly for CP3, the new flow is the sum of unappropriated flows at CP3 plus streamflow depletions at CP3, plus the fraction of the streamflow depletions made at all upstream control points that would have reached CP3:

$$1000+0+100*(1-0.1)*(1-0.1)+200(1-0.1)=1261$$

The resulting new inflows for the simplified dataset are shown in Figure 3.6.

In order to calculate the new inflows following the methodology just outlined, it is necessary to use WRAP-HYD to perform the streamflow adjustments.

The reader is directed to the Water Rights Analysis Package user's manual, (*4*), to learn about the file structure of WRAP-HYD.

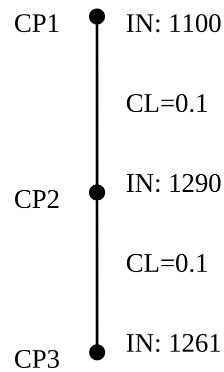


FIGURE 3.6 Resulting inflows for the naturalized flows example.

As mentioned previously, new “naturalized” flows are based on unappropriated flows and streamflow depletions on each control point included in the simplified dataset. It is necessary to build a file containing all unappropriated flows at each control point; this file has to follow the format for IN records. The author recommends the use of TABLES’s 3UNA record to build this file.

In order to perform all streamflow adjustments, AS records have to be created, these records define how the adjustments are done. Each control point included in the simplified dataset should have an AS record, a standard AS record should look like the following:

```
 1      2        3        4        5        6        7           8        9
--------------------------------------------------------------------
AS515631                          -1        0        0
```

Following each AS record, the streamflow depletions done at that control point should be included, these are the values generated from the 3DEP record in TABLES, in case of having upstream reservoirs making releases to downstream control points, streamflow depletions shown in the control point output file do not include those amounts, so it is necessary to check individual water rights to make sure all depletions are accounted.

Section 3.8.1 describes a special condition in which negative streamflow depletions exist. In that case it may be necessary to set up all flow adjustments in a spreadsheet package, such as Microsoft Excel.

After running WRAP-HYD, a new .FLO file containing “naturalized” flows for the simplified dataset is created.

3.8.1 Negative streamflow depletions

There is a possibility of having negative streamflow depletions at water rights or control points. If there is a month with a negative evaporation-precipitation depth, and the reservoir is full, then the reservoir will release water to the stream, being this release considered a negative streamflow depletion. When calculating the new “naturalized flows” a negative streamflow depletion can cause a negative “naturalized flow”; by default, WRAP converts any negative naturalized flow into zero, so additional water would be available at that control point. Also there is the possibility of creating significant negative incremental naturalized flows.

In order to avoid this situation, only positive streamflow depletions are considered, so that if a water right had a negative streamflow depletion, the control point streamflow depletion should be corrected by adding the absolute value of the negative streamflow depletion made by the water right. Consequently, only water taken from the river is accounted for. Part of the negative streamflow depletion, may have been used by other BRA water rights but the remainder may have been used by non BRA water rights. Since the simplified dataset will give the same results as the full dataset, negative streamflow depletions will duplicate during the simplified simulation, making this releases available only to BRA rights, increasing their reliabilities.

In order to take care of all negative streamflow depletions in the simplified dataset, a modeling strategy was developed to identify any negative streamflow depletions and take them out of the system (deplete them). Negative streamflow depletions occur on the most senior right in a reservoir, so a new water right with the same priority as the most senior right in a reservoir is added, but this right has two Target Options records, which set the target based on streamflow depletions made at the senior right. The target for the new right is equal to the absolute value of any negative streamflow depletion and zero otherwise. An example of this methodology is shown next for Lake Proctor.

```
WR515931   2685.    MUN219631216   1   2  0.0000             C5159_1
WSPRCTOR  59400.                               0
WR515931               19631216   2   2  0.0000             C5159_D
TO     6      -1                                      C5159_1    CONT
TO    10       1     MAX       0
```

Water right C5159_D depletes any negative streamflow depletion made by C5159_1, and avoids any junior right from having access to additional water.

3.9 PRELIMINARY RESULTS

Simplified datasets were built for the Brazos River Basin, using negative incremental naturalized flows options 4 and 5. The results obtained are shown in Tables 3.5 to 3.8. Results show that the reliabilities for the simplified simulation are similar to those of the complete one, but there are some differences for some of the upstream reservoirs.

3.10 COMPLEXITIES AND RESULTS

During the development and application of this methodology, several complexities arouse. Some of them can be fixed, but others are inherent to WRAP modeling procedures.

The first of the complexities has to do with downstream senior water rights that during the simplified simulation use the water that upstream junior water rights depleted during the complete simulation. As described in section 3.8, in order to calculate the new “naturalized” flows, the effect of all streamflow depletions is added downstream, resulting for any control point to have included in their “naturalized” flows all the unappropriated flows at that control point, streamflow depletions made at that control point and the effect of all upstream streamflow depletions. Theoretically, during the simplified simulation, all control points should deplete the same amount of water they depleted during the full simulation. In general, that is the case, but there are some exceptions.

TABLE 3.5 Reliabilities, After Running the Complete Dataset, Using NINF* Option 4

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY PERIOD (%)	RELIABILITY VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	>0%	PERCENTAGE OF YEARS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	98%	95%	90%	75%	50%	>0%
4146P1	35000	15369.51	49.86	56.09	49.9	50.7	51.1	52.3	54.5	58.5	100.0	29.3	29.3	29.3	31.0	32.8	51.7	100.0
421331	56000	5855.44	87.64	89.54	87.6	87.8	87.8	88.5	89.1	89.7	100.0	5.2	74.1	74.1	79.3	87.9	89.7	100.0
515531	230750	0.02	47.70	100.00	47.7	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	37.9	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	78.59	100.00	78.6	100.0	100.0	100.0	100.0	100.0	100.0	5.2	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	557.92	98.42	99.18	98.4	98.7	98.9	99.1	99.1	99.1	100.0	93.1	94.8	94.8	96.6	98.3	100.0	100.0
516231	13610	245.12	97.99	98.20	98.0	98.1	98.1	98.1	98.1	98.1	100.0	94.8	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	71.51	99.43	99.64	99.4	99.4	99.4	99.4	99.6	99.6	100.0	96.6	96.6	96.6	98.3	100.0	100.0	100.0
516431	48000	155.89	99.28	99.68	99.3	99.3	99.3	99.3	99.3	99.4	100.0	96.6	96.6	96.6	100.0	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	844770	22401.49		97.35														

TABLE 3.6 Reliabilities, After Running the Simplified Dataset, Using NINF* Option 4

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY PERIOD (%)	RELIABILITY VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	95%	90%	75%	50%	25%	>0%	PERCENTAGE OF YEARS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT 100%	98%	95%	90%	75%	50%	>0%
4146P1	35000	17108.18	45.11	51.12	45.1	45.7	46.1	46.8	49.1	52.9	100.0	22.4	22.4	24.1	27.6	29.3	44.8	100.0
421331	56000	7174.96	85.92	87.19	85.9	86.1	86.1	86.5	86.8	87.1	100.0	5.2	72.4	72.4	72.4	81.0	87.9	100.0
515531	230750	0.02	48.13	100.00	48.1	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	37.9	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	78.59	100.00	78.6	100.0	100.0	100.0	100.0	100.0	100.0	5.2	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	557.95	98.42	99.18	98.4	98.7	98.9	99.1	99.1	99.1	100.0	93.1	94.8	94.8	96.6	98.3	100.0	100.0
516231	13610	245.15	97.99	98.20	98.0	98.1	98.1	98.1	98.1	98.1	100.0	94.8	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	71.5	99.43	99.64	99.4	99.4	99.4	99.4	99.6	99.6	100.0	96.6	96.6	96.6	98.3	100.0	100.0	100.0
516431	48000	155.88	99.28	99.68	99.3	99.3	99.3	99.3	99.3	99.4	100.0	96.6	96.6	96.6	100.0	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	844770	25459.73		96.99														

* NINF = Negative Incremental Naturalized Flows

TABLE 3.7 Reliabilities, After Running the Complete Dataset, Using NINF* Option 5

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY		PERCENTAGE OF MONTHS							PERCENTAGE OF YEARS						
			PERIOD (%)	VOLUME (%)	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT													
					100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
4146P1	35000	17451.43	44.40	50.14	44.4	44.8	45.5	46.3	48.3	51.4	100.0	19.0	19.0	20.7	22.4	29.3	44.8	100.0
421331	56000	9074.01	82.04	83.80	82.0	82.2	82.2	83.0	83.6	84.2	100.0	5.2	67.2	69.0	69.0	74.1	84.5	100.0
515531	230750	0.02	47.41	100.00	47.4	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	41.4	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	77.16	100.00	77.2	100.0	100.0	100.0	100.0	100.0	100.0	3.4	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	500.86	98.71	99.26	98.7	98.9	98.9	99.1	99.3	99.3	100.0	94.8	94.8	96.6	96.6	98.3	100.0	100.0
516231	13610	229.43	98.13	98.31	98.1	98.1	98.1	98.1	98.3	98.4	100.0	93.1	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	53.85	99.57	99.73	99.6	99.6	99.6	99.6	99.6	99.7	100.0	96.6	96.6	98.3	98.3	100.0	100.0	100.0
516431	48000	228.8	99.14	99.52	99.1	99.1	99.1	99.1	99.1	99.3	100.0	96.6	96.6	96.6	96.6	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	844770	27684.47		96.72														

TABLE 3.8 Reliabilities, After Running the Simplified Dataset, Using NINF* Option 5

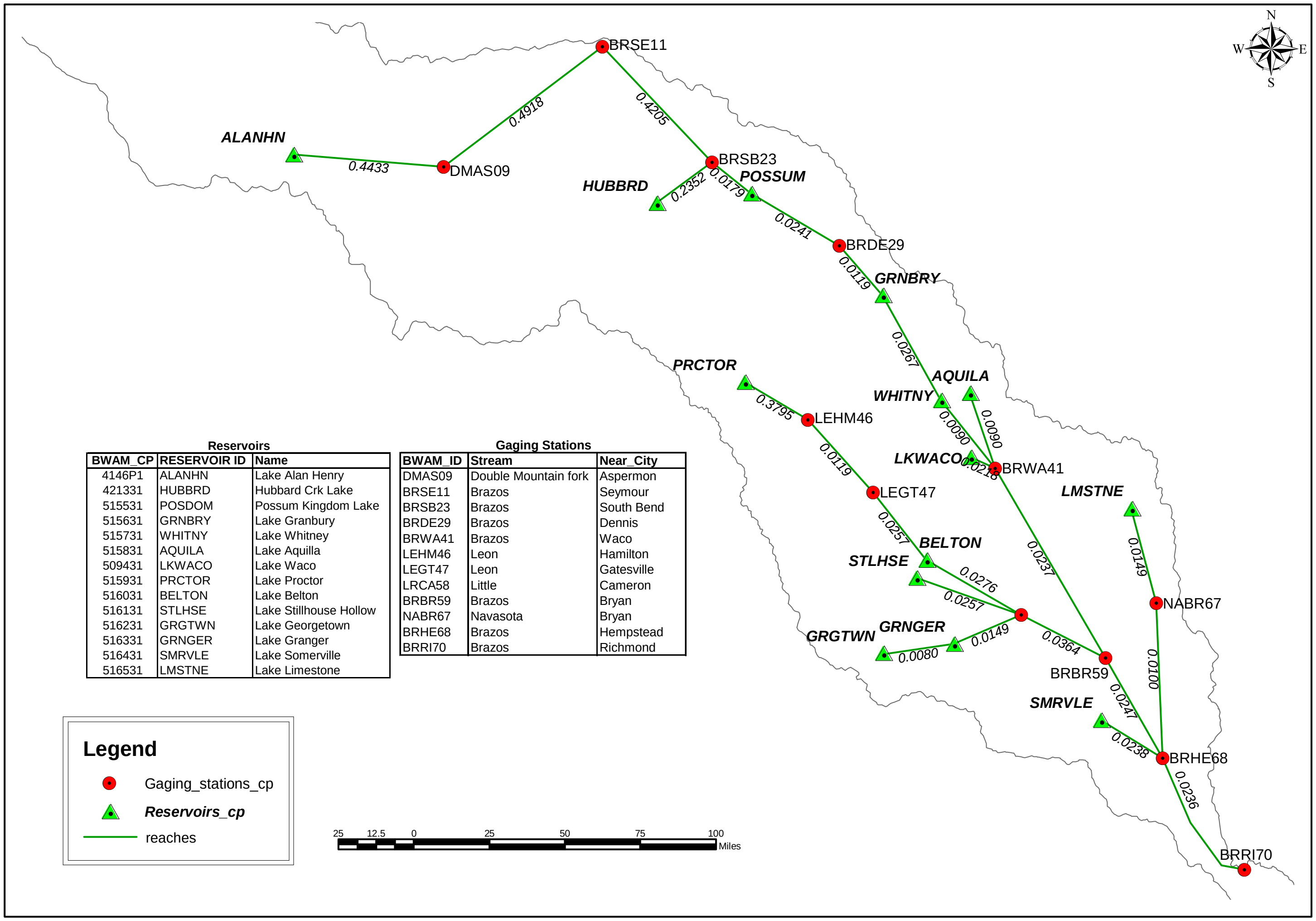
NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY		PERCENTAGE OF MONTHS							PERCENTAGE OF YEARS						
			PERIOD (%)	VOLUME (%)	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT													
					100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
4146P1	35000	17515.32	44.11	49.96	44.1	44.7	45.4	46.1	48.3	51.1	100.0	17.2	17.2	20.7	22.4	29.3	44.8	100.0
421331	56000	9107.69	81.90	83.74	81.9	82.0	82.2	82.9	83.6	84.1	100.0	5.2	67.2	69.0	69.0	74.1	84.5	100.0
515531	230750	0.02	47.41	100.00	47.4	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	41.4	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	77.16	100.00	77.2	100.0	100.0	100.0	100.0	100.0	100.0	3.4	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	500.92	98.71	99.26	98.7	98.9	98.9	99.1	99.3	99.3	100.0	94.8	94.8	96.6	96.6	98.3	100.0	100.0
516231	13610	229.46	98.13	98.31	98.1	98.1	98.1	98.1	98.3	98.4	100.0	93.1	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	53.84	99.57	99.73	99.6	99.6	99.6	99.6	99.6	99.7	100.0	96.6	96.6	98.3	98.3	100.0	100.0	100.0
516431	48000	228.77	99.14	99.52	99.1	99.1	99.1	99.1	99.1	99.3	100.0	96.6	96.6	96.6	96.6	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	844770	27782.1		96.71														

* NINF = Negative Incremental Naturalized Flows

In cases with extreme channel losses, there are big negative incremental flows; depending on the option used to take care of them, it is possible to have upstream junior water rights making depletions, even if a downstream senior water right depleted all the water available at its control point. This shouldn't occur, since there are no return flows returning on the same month and WRAP always checks downstream for any water available and if the senior right left none, then the junior right shouldn't have any available. As a consequence of this, when using the simplified dataset, the downstream senior water right will use the water that the upstream junior water right depleted during the complete simulation, and therefore leave less or none available to the junior water right, affecting its reliabilities and reservoir storage.

If negative incremental naturalized flows option 4 is being used, flows adjustments are considered by looking downstream of the control point in discussion, therefore this control point will not have access to any upstream negative incremental flow adjustments. On the other hand, when evaluating the upstream control point, this control point has access to additional flow adjustments that the downstream control point didn't (adjustments between both control points). It is because of this that the upstream junior water right is able to deplete water even tough the downstream senior right left none available.

This is the problem that occurred on the Brazos River Basin for Alan Henry, Hubbard Creek and Possum Kingdom, as well as Proctor and Belton reservoirs. As shown in Figure 3.7, the reach between Alan Henry and Possum Kingdom has a channel loss factor of 0.839, which means that 83.9% of the water that leaves Alan Henry is lost before it reaches Possum Kingdom. Similarly the reach between Hubbard Creek and Possum Kingdom has a channel loss factor of 0.248. Possum Kingdom is senior to both, Hubbard Creek and Allan Henry reservoirs, but due to the negative incremental flow adjustments that Alan Henry and Hubbard Creek have access to, they are able to deplete water that Possum Kingdom cannot have access to. During the simplified simulation, Possum Kingdom will have access to 16.1% of Allan Henry's depletions and 75% of Hubbard's depletions, therefore on months where Possum Kingdom reservoir is not full and Allan Henry or Hubbard Creek reservoirs made depletions (during the complete simulation), Possum Kingdom will have access to their water, resulting in higher reliabilities for Possum Kingdom and lower reliabilities and



Reservoirs

BWAM_CP	RESERVOIR ID	Name
4146P1	ALANHN	Lake Alan Henry
421331	HUBBRD	Hubbard Crk Lake
515531	POSDOM	Possum Kingdom Lake
515631	GRNBRY	Lake Granbury
515731	WHITNY	Lake Whitney
515831	AQUILA	Lake Aquilla
509431	LKWACO	Lake Waco
515931	PRCTOR	Lake Proctor
516031	BELTON	Lake Belton
516131	STLHSE	Lake Stillhouse Hollow
516231	GRGTWN	Lake Georgetown
516331	GRNGER	Lake Granger
516431	SMRVLE	Lake Somerville
516531	LMSTNE	Lake Limestone

Gaging Stations

BWAM_ID	Stream	Near_City
DMAS09	Double Mountain fork	Aspermon
BRSE11	Brazos	Seymour
BRSB23	Brazos	South Bend
BRDE29	Brazos	Dennis
BRWA41	Brazos	Waco
LEHM46	Leon	Hamilton
LEGT47	Leon	Gatesville
LRCA58	Little	Cameron
BRBR59	Brazos	Bryan
NABR67	Navasota	Bryan
BRHE68	Brazos	Hempstead
BRRI70	Brazos	Richmond

FIGURE 3.7 Channel losses in the Brazos River Basin.

reservoir storage for Alan Henry and Hubbard Creek.

If Negative Incremental Naturalized Flows (NINF) option 5 is used, upstream junior water rights will still be able to deplete water although downstream senior water rights left none available at the downstream control point. But with NINF option 5 this behavior is neither as frequent nor intense as the one shown by NINF option 4.

To compare both NINF options, graphics showing the differences in reservoir storage between the complete and the simplified simulations are shown in Figures 3.8 to 3.11, negative values indicate that during the simplified simulation the specific reservoir had a greater storage level than the one obtained during the complete simulation. On the other hand, positive values indicate a lower reservoir storage during the simplified simulation. Table 3.9 shows the maximum and minimum differences in storage level for all the reservoirs included in the simplified dataset, when using NINF # 4 or 5.

TABLE 3.9`Maximum and Minimum Differences in Storage for NINF 4 or 5 (ac-ft)

	NINF 4		NINF 5	
Reservoir	max	min	max	min
ALANHN	36846.9	-1.3	1933.7	-1.1
HUBBRD	37301.8	-0.8	1461.6	-1.4
POSDOM	1.7	-14787.5	1.8	-1250.9
PRCTOR	1370.6	-2.3	123.8	-8.4
GRNBRY	416.9	-13751.3	2.1	-839.1
WHITNY	293.4	-13311.1	1.3	-6629.9
AQUILA	2.5	-1.5	2.2	-1.5
LKWACO	1.5	-4.5	1.8	-2544.6
BELTON	1.8	-870.6	1.5	-74.6
STLHSE	1.9	-2.8	2.7	-1.9
GRGTWN	2.9	-2.4	2.6	-2.4
GRNGER	1.8	-1.7	1.8	-1.6
SMRVLE	1.9	-37.5	1.9	-37.5
LMSTNE	2.1	-5.5	1.6	-5.5

As described previously, while Possum Kingdom increases its storage level, Hubbard Creek and Alan Henry are affected negatively. While with NINF option 4, the maximum negative impact on Alan Henry and Hubbard Creek is around 37,000 Ac-ft

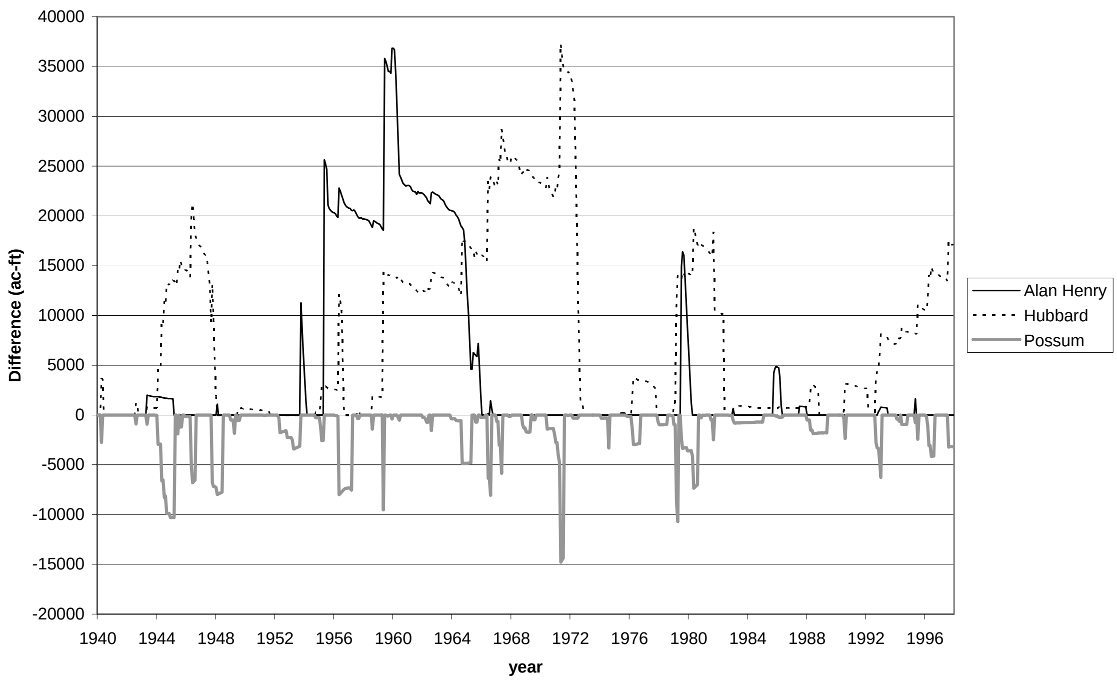


FIGURE 3.8 Storage differences between the complete and simplified simulation using NINF #4 for reservoirs Alan Henry, Hubbard Creek and Possum Kingdom.

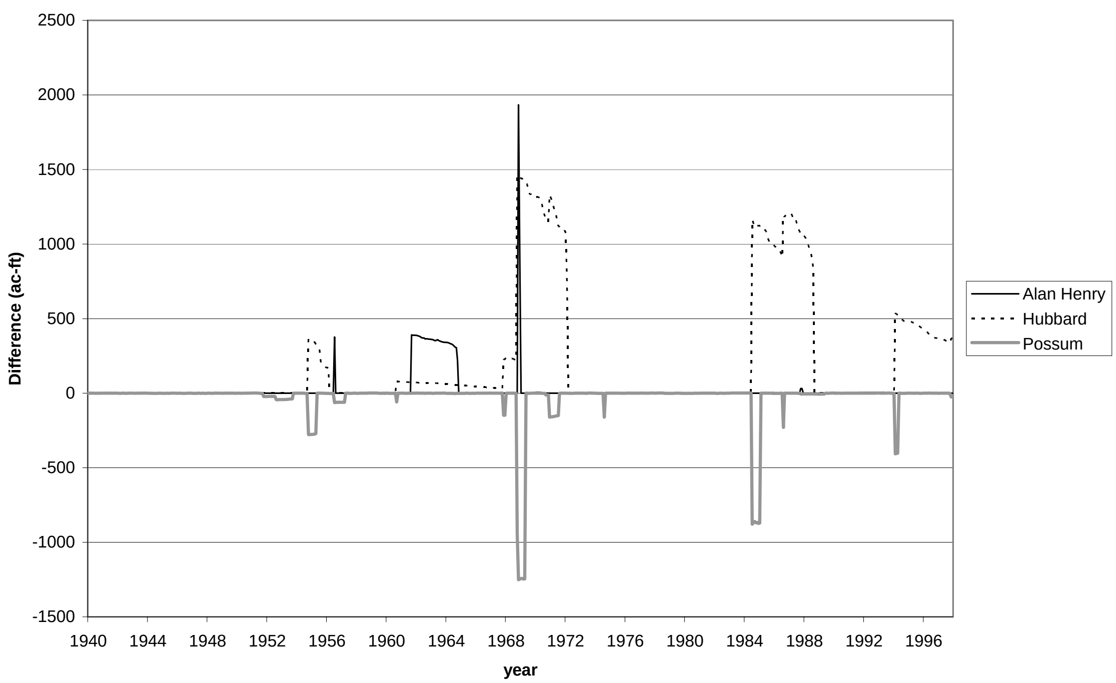


FIGURE 3.9 Storage differences between the complete and simplified simulation using NINF # 5 for reservoirs Alan Henry, Hubbard Creek and Possum Kingdom.

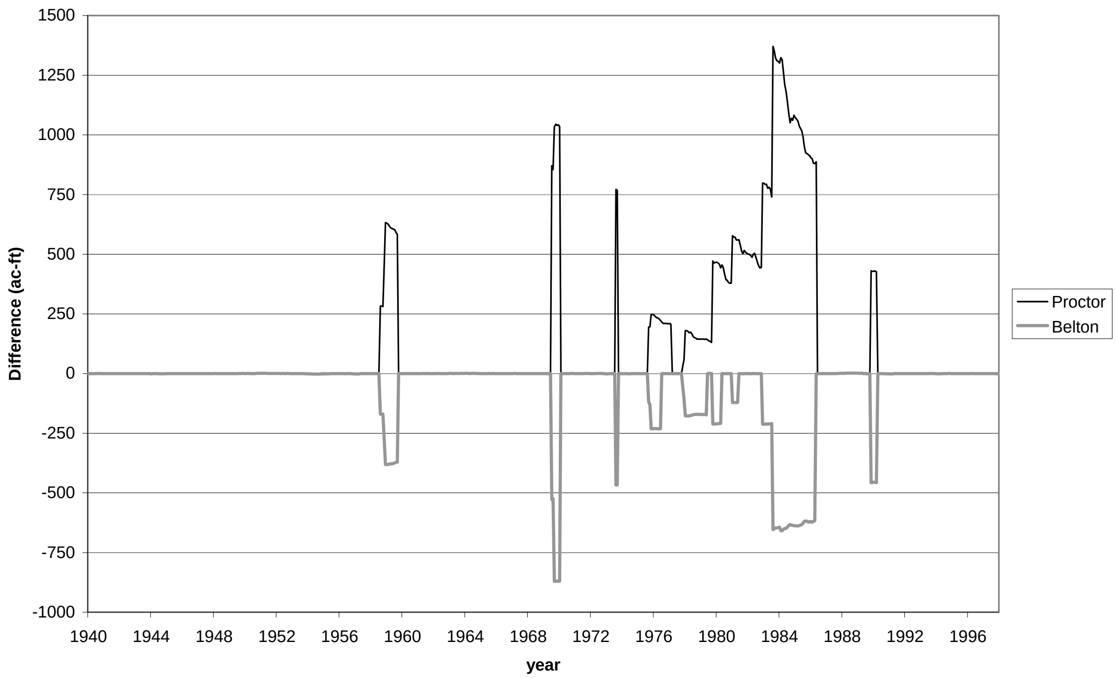


FIGURE 3.10 Storage differences between the complete and simplified simulation using NINF # 4 for Lakes Proctor and Belton.

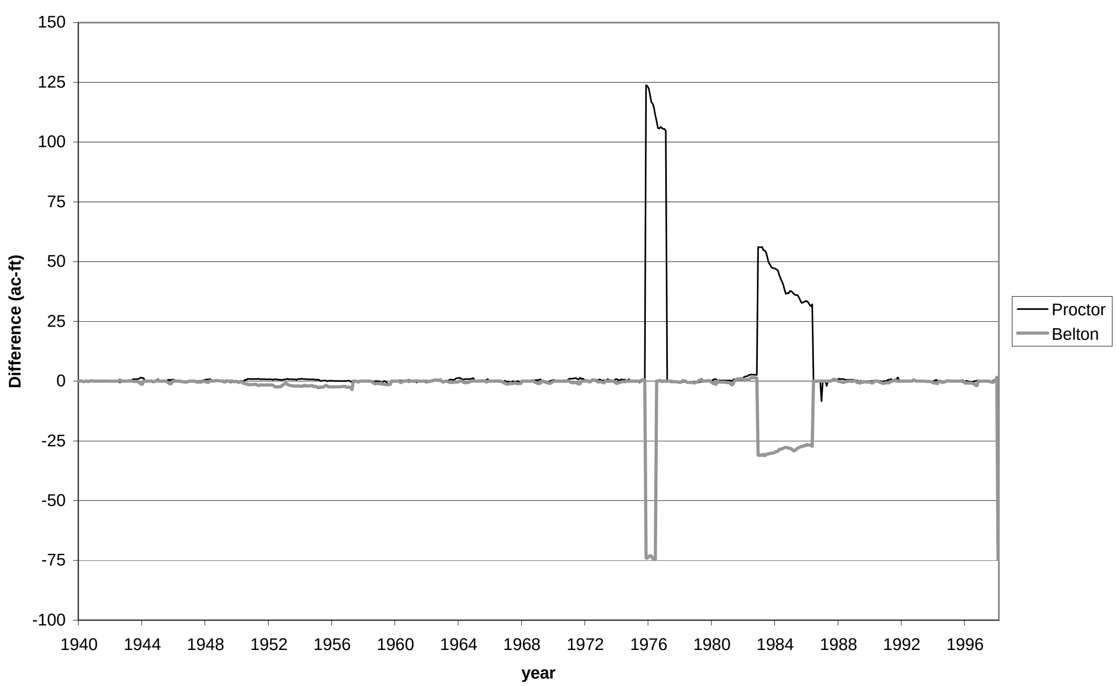


FIGURE 3.11 Storage differences between the complete and simplified simulation using NINF # 5 for Lakes Proctor and Belton.

and on Possum Kingdom around 15,000 ac-ft, when NINF option 5 is used, these values decrease to 1,900 and 1,300 respectively. This proves that with NINF option 5 and in the case of extreme channel losses, upstream junior water rights have less chance to deplete water once a downstream senior water right has left none available, than when using NINF option 4.

A similar problem occurs with Lake Proctor and Lake Belton. Proctor is junior to Belton and is located upstream of it, as well as with Alan Henry and Possum Kingdom, the channel losses in the reach between Proctor and Belton are close to 40%. As shown in Figures 3.10 and 3.11, the impact when using NINF option 5 is less than when using NINF option 4.

A new simplified dataset was created, this time excluding Alan Henry and Hubbard Creek reservoirs. Reliability results for this simulation are shown in Tables 3.10 to 3.13. For both NINF options, the control point reliabilities are the same, but when analyzing storage time series, some differences arise. For NINF options 4 and 5, the storage levels at Possum Kingdom were the same during both, the complete and the simplified simulations.

When using NINF option 5, the differences in Proctor decreased compared to the ones observed with the dataset that included Alan Henry and Hubbard Creek. This means that although Alan Henry and Hubbard Creek reservoirs are neither upstream nor downstream of Proctor, they have an effect over it (subject to using NINF option 5). If NINF # 4 is used, the differences in storage levels remain the same as when Alan Henry and Hubbard Creek reservoirs were included in the simplified simulation. Table 3.14 shows the maximum and minimum differences in storage levels for the simplified simulation that excluded Alan Henry and Hubbard Creek reservoirs. Figures 3.12 and 3.13 show the differences in storage levels for Proctor and Belton, when using NINF options 4 and 5.

TABLE 3.10 Reliabilities, After Running the Complete Dataset, Using NINF* Option 4

NAME	TARGET	MEAN	RELIABILITY		PERCENTAGE OF MONTHS							PERCENTAGE OF YEARS						
	DIVERSION	SHORTAGE	PERIOD	VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT													
	(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.70	100.00	47.7	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	37.9	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	78.59	100.00	78.6	100.0	100.0	100.0	100.0	100.0	100.0	5.2	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	557.92	98.42	99.18	98.4	98.7	98.9	99.1	99.1	99.1	100.0	93.1	94.8	94.8	96.6	98.3	100.0	100.0
516231	13610	245.12	97.99	98.20	98.0	98.1	98.1	98.1	98.1	98.1	100.0	94.8	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	71.51	99.43	99.64	99.4	99.4	99.4	99.4	99.6	99.6	100.0	96.6	96.6	96.6	98.3	100.0	100.0	100.0
516431	48000	155.89	99.28	99.68	99.3	99.3	99.3	99.3	99.3	99.4	100.0	96.6	96.6	96.6	100.0	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	753770	1176.53		99.84														

TABLE 3.11 Reliabilities, After Running the Simplified Dataset Without Alan Henry and Hubbard Creek, Using NINF* option 4

NAME	TARGET	MEAN	RELIABILITY		PERCENTAGE OF MONTHS							PERCENTAGE OF YEARS						
	DIVERSION	SHORTAGE	PERIOD	VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT													
	(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.70	100.00	47.7	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	37.9	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	78.59	100.00	78.6	100.0	100.0	100.0	100.0	100.0	100.0	5.2	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	557.95	98.42	99.18	98.4	98.7	98.9	99.1	99.1	99.1	100.0	93.1	94.8	94.8	96.6	98.3	100.0	100.0
516231	13610	245.15	97.99	98.20	98.0	98.1	98.1	98.1	98.1	98.1	100.0	94.8	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	71.5	99.43	99.64	99.4	99.4	99.4	99.4	99.6	99.6	100.0	96.6	96.6	96.6	98.3	100.0	100.0	100.0
516431	48000	155.88	99.28	99.68	99.3	99.3	99.3	99.3	99.3	99.4	100.0	96.6	96.6	96.6	100.0	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	753770	1176.59		99.84														

* NINF = Negative Incremental Naturalized Flows

TABLE 3.12 Reliabilities, After Running the Complete Dataset, Using NINF* Option 5

NAME	TARGET	MEAN	RELIABILITY		PERCENTAGE OF MONTHS							PERCENTAGE OF YEARS						
	DIVERSION	SHORTAGE	PERIOD	VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT													
	(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.41	100.00	47.4	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	41.4	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	77.16	100.00	77.2	100.0	100.0	100.0	100.0	100.0	100.0	3.4	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	500.86	98.71	99.26	98.7	98.9	98.9	99.1	99.3	99.3	100.0	94.8	94.8	96.6	96.6	98.3	100.0	100.0
516231	13610	229.43	98.13	98.31	98.1	98.1	98.1	98.1	98.3	98.4	100.0	93.1	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	53.85	99.57	99.73	99.6	99.6	99.6	99.6	99.6	99.7	100.0	96.6	96.6	98.3	98.3	100.0	100.0	100.0
516431	48000	228.8	99.14	99.52	99.1	99.1	99.1	99.1	99.1	99.3	100.0	96.6	96.6	96.6	96.6	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	753770	1159.03		99.85														

TABLE 3.13 Reliabilities, After Running the Simplified Dataset Without Alan Henry and Hubbard Creek, Using NINF* Option 5

NAME	TARGET	MEAN	RELIABILITY		PERCENTAGE OF MONTHS							PERCENTAGE OF YEARS						
	DIVERSION	SHORTAGE	PERIOD	VOLUME	WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT													
	(AC-FT/YR)	(AC-FT/YR)	(%)	(%)	100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.41	100.00	47.4	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	41.4	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
515931	19658	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	77.16	100.00	77.2	100.0	100.0	100.0	100.0	100.0	100.0	3.4	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	500.92	98.71	99.26	98.7	98.9	98.9	99.1	99.3	99.3	100.0	94.8	94.8	96.6	96.6	98.3	100.0	100.0
516231	13610	229.46	98.13	98.31	98.1	98.1	98.1	98.1	98.3	98.4	100.0	93.1	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	53.84	99.57	99.73	99.6	99.6	99.6	99.6	99.6	99.7	100.0	96.6	96.6	98.3	98.3	100.0	100.0	100.0
516431	48000	228.77	99.14	99.52	99.1	99.1	99.1	99.1	99.1	99.3	100.0	96.6	96.6	96.6	96.6	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	753770	1159.09		99.85														

* NINF = Negative Incremental Naturalized Flows

TABLE 3.14 Maximum and Minimum Differences in Storage for NINF 4 or 5, Without Alan Henry and Hubbard Creek

	NINF 4		NINF 5	
Reservoir	max	min	max	min
POSDOM	2.9	-1.4	2.4	-1.3
PRCTOR	1370.6	-2.3	40.3	-8.4
GRNBRY	2.8	-2.3	2.8	-340.2
WHITNY	1.3	-2.8	333.5	-3.5
AQUILA	2.5	-1.5	2.2	-1.5
LKWACO	1.5	-4.5	1.8	-2544.6
BELTON	1.8	-870.6	1.7	-74.6
STLHSE	1.9	-2.8	2.7	-1.9
GRGTWN	2.9	-2.4	2.6	-2.4
GRNGER	1.8	-1.7	1.8	-1.6
SMRVLE	1.9	-37.5	1.9	-37.5
LMSTNE	2.1	-5.5	1.6	-5.5

FIGURE 3.12 Storage differences between the complete and simplified simulation using NINF # 4 for Lakes Proctor and Belton, simulation without Alan Henry or Hubbard Creek.

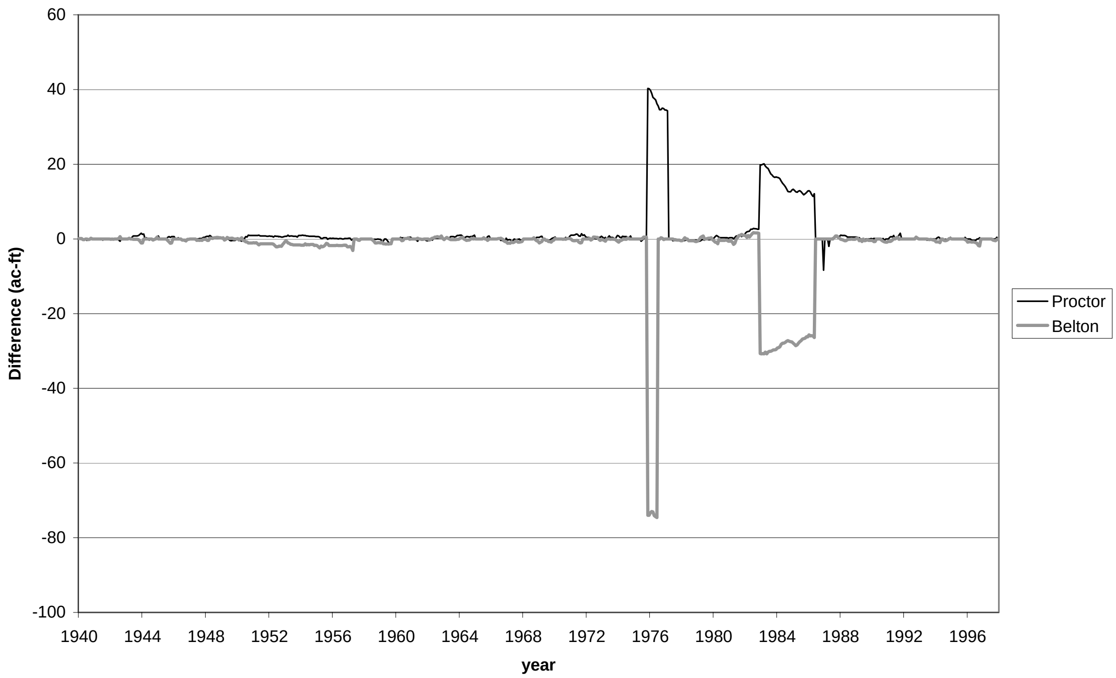


FIGURE 3.13 Storage differences between the complete and simplified simulation using NINF # 5 for Lakes Proctor and Belton, simulation without Alan Henry or Hubbard Creek.

When analyzing Granbury and Whitney reservoirs, if NINF option 4 is used, the previously enormous differences, no longer exist. While if NINF option 5 is used, the positive storage level differences obtained for Whitney during the simplified simulation are corrected, but the negative differences increased. The reason for this is that during the complete simulation, Granbury which is senior and located upstream of Whitney, couldn't meet its demands, but left unappropriated flows at the end of the simulation. Whitney met all its needs by making depletions, but since it is located downstream of Granbury, when calculating new "naturalized flows", Whitney's depletions are not added to Granbury's "naturalized flows". During the simplified simulation, for some reason, Granbury had access to the unappropriated flows left during the complete simulation, and as a consequence it affected the amount of water available to Whitney. This situation only happened once during the simulation, as shown in Figure 3.14.

A similar problem occurred for Lake Waco, where for one month of the full simulation, when using NINF option 5, it couldn't meet all the demands from streamflow depletions, but left unappropriated flows. During the simplified simulation, Lake Waco had access to these unappropriated flows and therefore depleted them, increasing its final storage level without affecting other water rights. Because of this, it is not considered a problem.

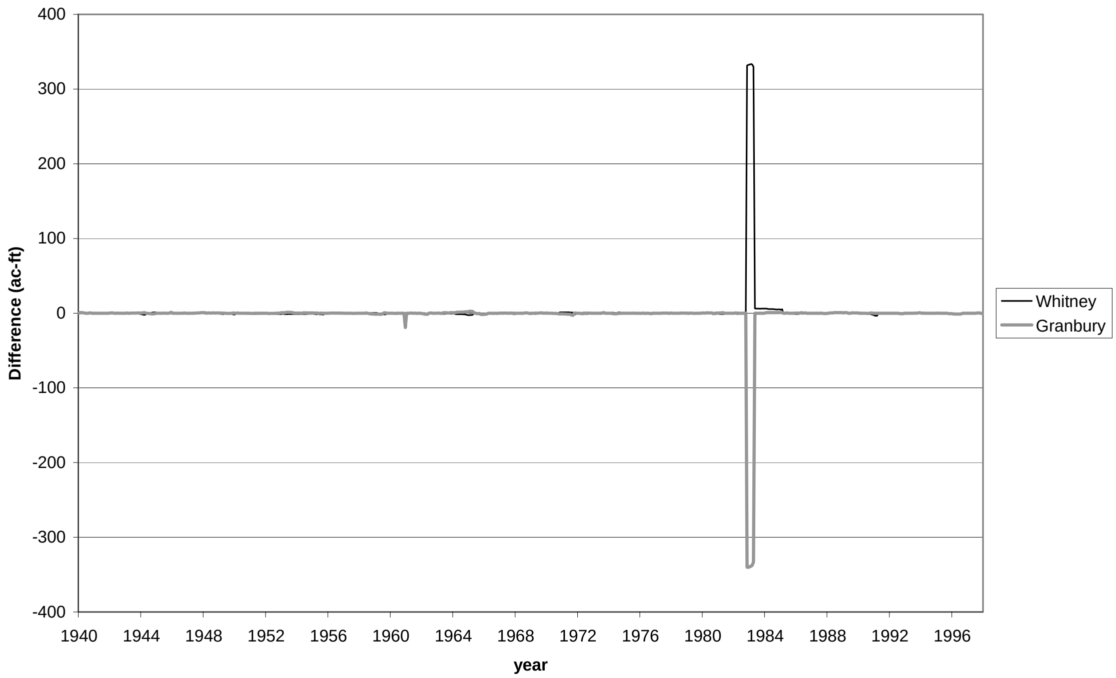


FIGURE 3.14 Storage differences between the complete and simplified simulation using NINF # 5 for Whitney and Granbury, simulation without Alan Henry or Hubbard Creek.

The only difference remaining is the one involving Proctor and Belton reservoirs. As with Allan Henry and Hubbard Creek, the solution was to remove Proctor reservoir from the simplified dataset. The reliabilities obtained from this new simplified dataset are shown in Tables 3.15 to 3.18. Once again, the reliabilities between the complete and the simplified simulation are almost the same. When analyzing storage differences, it is noticed that the differences for Belton are fixed; the remaining differences have already been discussed and have no major impact on the results. Table 3.19 shows the maximum and minimum differences in storage levels for the simplified simulation that excluded Alan Henry, Hubbard Creek and Proctor reservoirs.

TABLE 3.15 Reliabilities, After Running the Complete Dataset, Using NINF* Option 4

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY PERIOD (%)	RELIABILITY VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT							PERCENTAGE OF YEARS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						
					100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.70	100.00	47.7	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	37.9	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	78.59	100.00	78.6	100.0	100.0	100.0	100.0	100.0	100.0	5.2	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	557.92	98.42	99.18	98.4	98.7	98.9	99.1	99.1	99.1	100.0	93.1	94.8	94.8	96.6	98.3	100.0	100.0
516231	13610	245.12	97.99	98.20	98.0	98.1	98.1	98.1	98.1	98.1	100.0	94.8	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	71.51	99.43	99.64	99.4	99.4	99.4	99.4	99.6	99.6	100.0	96.6	96.6	96.6	98.3	100.0	100.0	100.0
516431	48000	155.89	99.28	99.68	99.3	99.3	99.3	99.3	99.3	99.4	100.0	96.6	96.6	96.6	100.0	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	734112	1176.53		99.84														

TABLE 3.16 Reliabilities, After Running the Simplified Dataset Without Alan Henry, Hubbard Creek and Proctor, Using NINF* 4

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY PERIOD (%)	RELIABILITY VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT							PERCENTAGE OF YEARS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						
					100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.70	100.00	47.7	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	37.9	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	78.59	100.00	78.6	100.0	100.0	100.0	100.0	100.0	100.0	5.2	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	557.95	98.42	99.18	98.4	98.7	98.9	99.1	99.1	99.1	100.0	93.1	94.8	94.8	96.6	98.3	100.0	100.0
516231	13610	245.15	97.99	98.20	98.0	98.1	98.1	98.1	98.1	98.1	100.0	94.8	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	71.5	99.43	99.64	99.4	99.4	99.4	99.4	99.6	99.6	100.0	96.6	96.6	96.6	98.3	100.0	100.0	100.0
516431	48000	155.88	99.28	99.68	99.3	99.3	99.3	99.3	99.3	99.4	100.0	96.6	96.6	96.6	100.0	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	734112	1176.59		99.84														

* NINF = Negative Incremental Naturalized Flows

TABLE 3.17 Reliabilities, After Running the Complete Dataset, Using NINF* Option 5

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY PERIOD (%)	RELIABILITY VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT							PERCENTAGE OF YEARS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						
					100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.41	100.00	47.4	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	41.4	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	77.16	100.00	77.2	100.0	100.0	100.0	100.0	100.0	100.0	3.4	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	500.86	98.71	99.26	98.7	98.9	98.9	99.1	99.3	99.3	100.0	94.8	94.8	96.6	96.6	98.3	100.0	100.0
516231	13610	229.43	98.13	98.31	98.1	98.1	98.1	98.1	98.3	98.4	100.0	93.1	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	53.85	99.57	99.73	99.6	99.6	99.6	99.6	99.6	99.7	100.0	96.6	96.6	98.3	98.3	100.0	100.0	100.0
516431	48000	228.8	99.14	99.52	99.1	99.1	99.1	99.1	99.1	99.3	100.0	96.6	96.6	96.6	96.6	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	734112	1159.03		99.84														

TABLE 3.18 Reliabilities, After Running the Simplified Dataset Without Alan Henry, Hubbard Creek and Proctor, Using NINF* 5

NAME	TARGET DIVERSION (AC-FT/YR)	MEAN SHORTAGE (AC-FT/YR)	RELIABILITY PERIOD (%)	RELIABILITY VOLUME (%)	PERCENTAGE OF MONTHS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT							PERCENTAGE OF YEARS WITH DIVERSIONS EQUALING OR EXCEEDING PERCENTAGE OF TARGET DIVERSION AMOUNT						
					100%	95%	90%	75%	50%	25%	>0%	100%	98%	95%	90%	75%	50%	>0%
515531	230750	0.02	47.41	100.00	47.4	100.0	100.0	100.0	100.0	100.0	100.0	1.7	100.0	100.0	100.0	100.0	100.0	100.0
515631	64712	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	41.4	100.0	100.0	100.0	100.0	100.0	100.0
515731	18336	146.06	98.85	99.20	98.9	98.9	98.9	98.9	98.9	98.9	100.0	96.6	96.6	96.6	96.6	98.3	100.0	100.0
515831	13896	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
509431	79869	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
516031	112257	0.01	77.16	100.00	77.2	100.0	100.0	100.0	100.0	100.0	100.0	3.4	100.0	100.0	100.0	100.0	100.0	100.0
516131	67768	500.92	98.71	99.26	98.7	98.9	98.9	99.1	99.3	99.3	100.0	94.8	94.8	96.6	96.6	98.3	100.0	100.0
516231	13610	229.46	98.13	98.31	98.1	98.1	98.1	98.1	98.3	98.4	100.0	93.1	94.8	94.8	94.8	98.3	98.3	100.0
516331	19840	53.84	99.57	99.73	99.6	99.6	99.6	99.6	99.6	99.7	100.0	96.6	96.6	98.3	98.3	100.0	100.0	100.0
516431	48000	228.77	99.14	99.52	99.1	99.1	99.1	99.1	99.1	99.3	100.0	96.6	96.6	96.6	96.6	100.0	100.0	100.0
516531	65074	0	100.00	100.00	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Total	734112	1159.09		99.84														

* NINF = Negative Incremental Naturalized Flows

TABLE 3.19 Maximum and Minimum Differences in Storage for NINF 4 or 5, Without Alan Henry, Hubbard Creek and Proctor Reservoirs

	NINF 4		NINF 5	
Reservoir	max	min	max	min
POSDOM	2.9	-1.4	2.4	-1.3
GRNBRY	2.8	-2.3	2.8	-340.2
WHITNY	1.3	-2.8	333.5	-3.5
AQUILA	2.5	-1.5	2.2	-1.5
LKWACO	1.5	-4.5	1.8	-2544.6
BELTON	1.8	-1.9	3.4	-1.9
STLHSE	1.9	-2.8	2.7	-1.9
GRGTWN	2.9	-2.4	2.6	-2.4
GRNGER	1.8	-1.7	1.8	-1.6
SMRVLE	1.9	-37.5	1.9	-37.5
LMSTNE	2.1	-5.5	1.6	-5.5

The final configuration of the simplified dataset guarantees an almost exact reproduction of the full simulation results, which means that it represents satisfactorily the effect of all the other hundreds of control points and water rights. The amount of water used in the simplified simulation corresponds to the water available to develop new permits and all the water already allocated to the reservoirs included in the simulation.

If the objective of the development of the simplified dataset is to study the effect of different operating policies in the Brazos River Authority (BRA) system, then the original dataset (including Alan Henry, Hubbard Creek and Proctor reservoirs) would be useful, since it already includes all the water allocated to the BRA system and any decrease in reliabilities for a specific reservoir would be translated into increasing reliabilities at another BRA reservoir.

Figure 3.15 shows the final configuration of the simplified dataset for the Brazos River Basin.

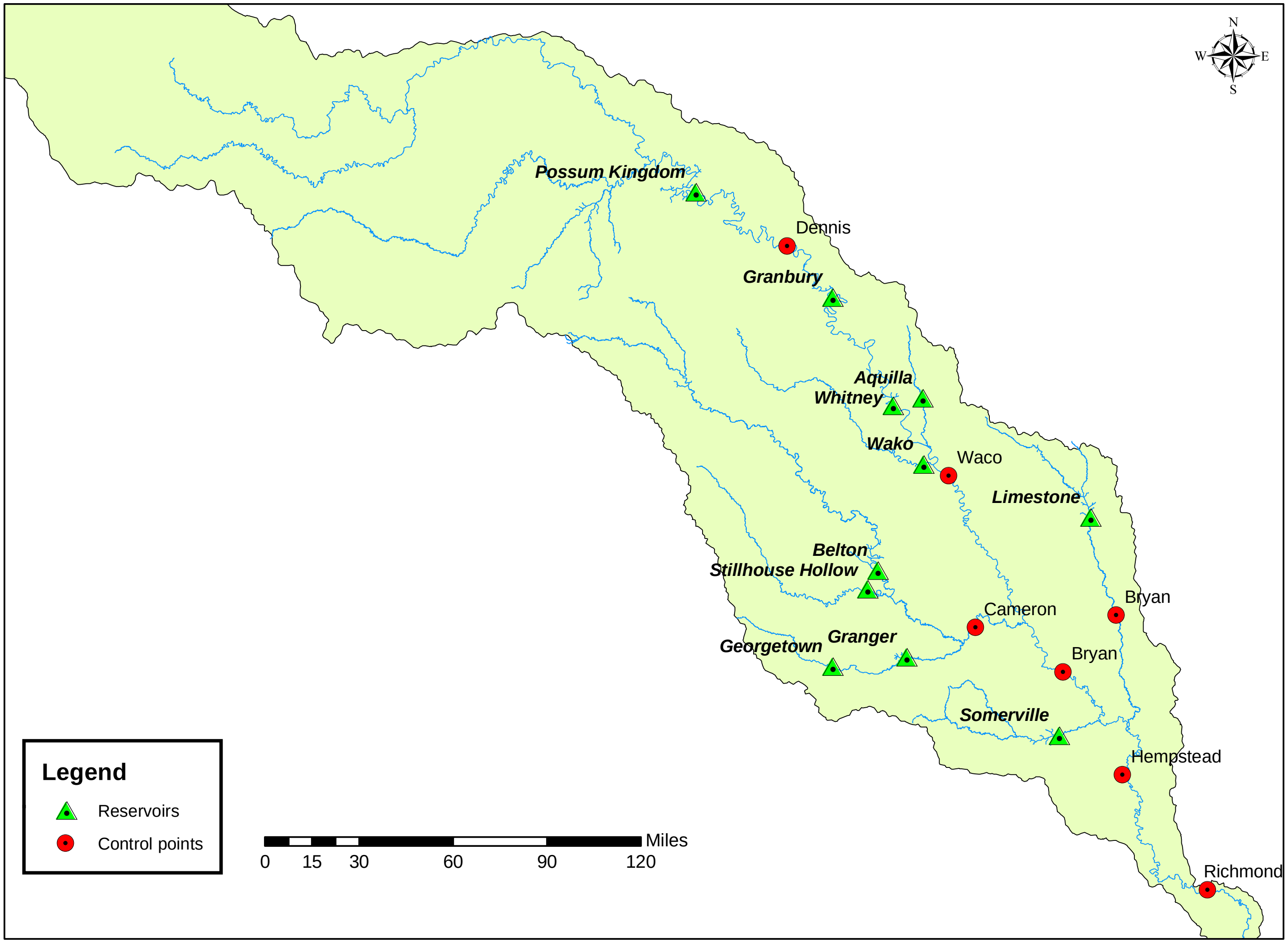


FIGURE 3.15 Final configuration for the Brazos River Basin simplified dataset.

3.11 APPLICATIONS OF THE SIMPLIFIED DATASET

The simplified dataset may have several applications, such as:

- Calculation of firm yields at individual reservoirs
- Calculation of firm yields with reservoir operated as a system
- Testing of new modeling strategies

All of these applications would require special modeling techniques, while with the simplified dataset they could be easily modeled. Chapter 4 deals with these applications and compares results obtained with a full dataset and alternative modeling approaches.

CHAPTER IV

YIELD-RELIABILITY ANALYSES FOR ALTERNATIVE SYSTEM MANAGEMENT STRATEGIES AND MODELING PREMISES

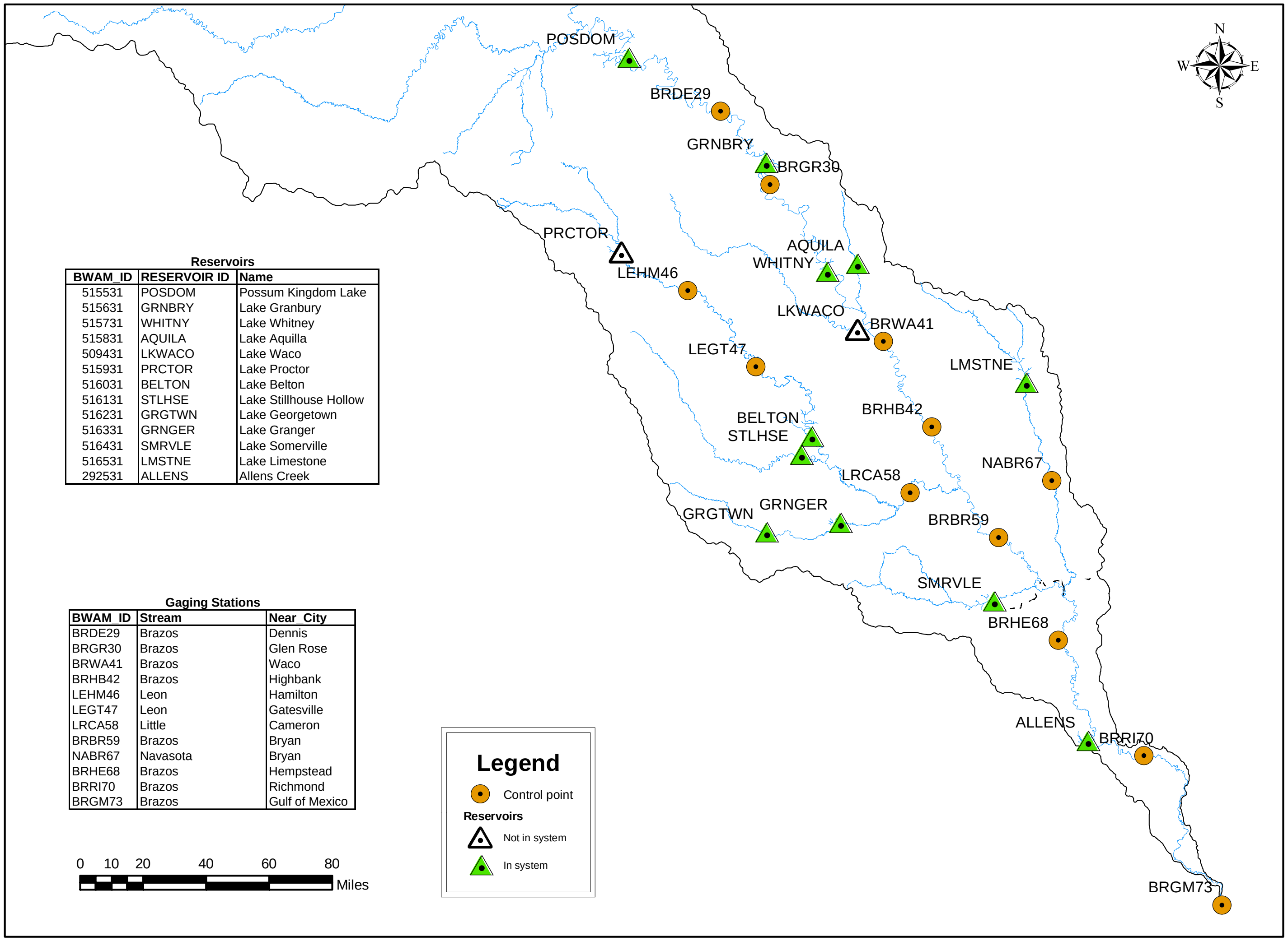
The objective of this chapter is to explore different methodologies and approaches to model single-reservoir and multiple-reservoir yields, without affecting other non system water rights but considering their effect on the system.

The development of a simplified dataset was described on chapter 3 of this document, in this chapter it will be applied to the proposed Brazos River Authority (BRA) system. The simplified dataset is based on the full authorization WAM dataset for the Brazos River Basin, available at the TCEQ web site. This simplified dataset consists of 13 reservoirs and 26 control points, shown in Figure 4.1; Table 4.1 lists the reservoirs included in the system, with their properties.

TABLE 4.1 Reservoirs Included in the System

Reservoir	County	Owner	Year completed	Conservation storage (Ac-Ft)	Permitted Diversion (Ac-Ft/yr)
Possum kingdom	Palo Pinto	BRA	1941	724,739	230,750
Granbury	Hood	BRA	1969	155,000	64,712
Whitney	Hill and Bosque	USACE	1951	50,000	18,336
Aquila	Hill	USACE	1983	52,400	13,896
Belton	Bell	USACE	1954	457,600	112,257
Stillhouse Hollow	Bell	USACE	1968	235,700	67,768
Georgetown	Williamson	USACE	1980	37,100	13,610
Granger	Williamson	USACE	1980	65,500	19,840
Somerville	Burleson and Washington	USACE	1967	160,110	48,000
Limestone	Leon, Limestone and Robertson	BRA	1970	225,400	65,074
Allens Creek	Austin	BRA, Houston and TWDB	Not constructed	145,533	99,650

Lake Allan Henry was not included in the system since it is located far upstream in the basin and channel losses to Possum Kingdom reservoir exceed 83%, so it is not feasible to make releases to any of the system diversion locations.



Reservoirs

BWAM_ID	RESERVOIR ID	Name
515531	POSDOM	Possum Kingdom Lake
515631	GRNBRY	Lake Granbury
515731	WHITNY	Lake Whitney
515831	AQUILA	Lake Aquilla
509431	LKWACO	Lake Waco
515931	PRCTOR	Lake Proctor
516031	BELTON	Lake Belton
516131	STLHSE	Lake Stillhouse Hollow
516231	GRGTWN	Lake Georgetown
516331	GRNGER	Lake Granger
516431	SMRVLE	Lake Somerville
516531	LMSTNE	Lake Limestone
292531	ALLENS	Allens Creek

Gaging Stations

BWAM_ID	Stream	Near_City
BRDE29	Brazos	Dennis
BRGR30	Brazos	Glen Rose
BRWA41	Brazos	Waco
BRHB42	Brazos	Highbank
LEHM46	Leon	Hamilton
LEGT47	Leon	Gatesville
LRCA58	Little	Cameron
BRBR59	Brazos	Bryan
NABR67	Navasota	Bryan
BRHE68	Brazos	Hempstead
BRRI70	Brazos	Richmond
BRGM73	Brazos	Gulf of Mexico

FIGURE 4.1 Reservoirs included in the simplified dataset.

Lake Proctor was not included in the system, since in reality no releases are made from Proctor to any of the system locations. Although it was included in the simplified dataset, it is not part of the system.

Lake Waco was not included in the system, since all of its rights are held by the city of Waco. As Lake Proctor, it was included in the simplified dataset.

4.1 SINGLE RESERVOIR YIELD-RELIABILITY TABLES FOR EACH BRA RESERVOIR

In this approach, the simplified dataset developed for the BRA system was modified to analyze only a specific reservoir in each run (13 different runs). In case of having one or more reservoirs located upstream of the one in study, these upstream reservoirs were included as senior reservoirs, diverting their firm yield. Any other water rights were removed from the simulation.

For example, when evaluating Lake Whitney, only Possum Kingdom and Granbury reservoirs were included, Possum Kingdom was senior to Granbury and Granbury was senior to Whitney; these reservoirs diverted their firm yield.

Each reservoir in turn, had access only to BRA water and unappropriated flows, no non BRA water rights (over 1,000 rights) were affected. In order to be able to compare results with further simulations, a unique set of water use coefficients was developed, by weighting all the BRA demands and the various sets of water use coefficients used. Water use coefficients vary with type of use and location within the basin. The Brazos river basin is divided into four subbasins: Upper, upper middle, lower middle and lower basin. Figure 4.2 shows the location of each reservoir, control points and subbasins. Table 4.2 summarizes user coefficients and target amounts per subbasin; these values along with the different sets of water use coefficients were used to calculate the weighted water use coefficients.

Two scenarios were evaluated, the first one including Allens Creek reservoir and the second one without including it. Based on these premises, a yield-reliability table was developed for each reservoir. Results are shown in Table 4.3 for the scenario including Allens Creek reservoir, and in Table 4.4 for the scenario without Allens Creek.

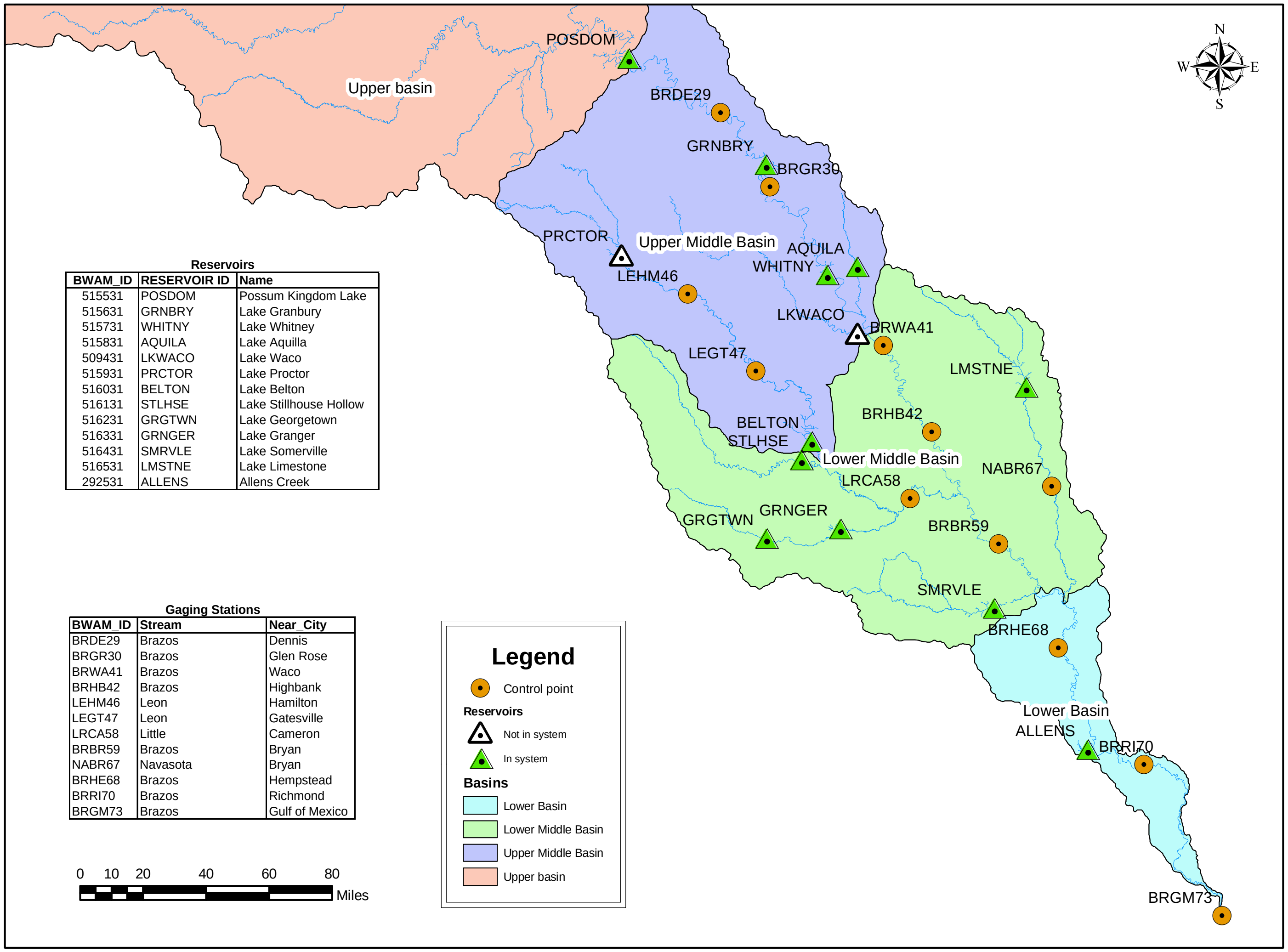
TABLE 4.2 Water Use Coefficients, Target Amounts per Subbasin and Weighted Water Use Coefficients

Basin	User Coef	Target	Total Basin	% target
Upper middle basin	MUN2	279,524	539,478	63.21
	IND2	197,398		
	IRR2	39,857		
	MIN2	19,099		
	HYD2	3,600		
Lower middle basin	MUN3	127,899	214,292	25.11
	IRR3	13,802		
	IND3	72,537		
	MIN3	54		
Lower basin	MUN4	99,650	99,650	11.68
		Total	853,420	100.00

jan	feb	mar	apr	may	jun
0.058	0.061	0.068	0.075	0.089	0.105
jul	**aug**	**sep**	**oct**	**nov**	**dec**
0.125	0.118	0.095	0.079	0.066	0.061

TABLE 4.3 Yield-Reliability for Individual Reservoirs, Including Allens Creek

Reservoir	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Possum kingdom	310,180	373,857	403,571	441,200	535,000
Lake Granbury	70,855	89,928	111,930	138,896	211,802
Lake Whitney	11,900	27,892	45,678	94,465	218,500
Lake Proctor	21,135	23,724	27,965	35,430	52,081
Lake Belton	115,560	128,407	159,421	203,295	323,500
Lake Stillhouse Hollow	63,380	69,965	90,896	117,600	176,500
Lake Georgetown	11,527	13,741	17,302	22,311	36,750
Lake Granger	19,000	23,302	30,948	44,649	84,325
Lake Aquilla	14,280	19,777	25,753	33,515	55,860
Lake Waco	93,100	106,928	123,785	160,209	242,000
Lake Limestone	66,770	81,928	98,896	133,860	207,000
Lake Somerville	43,470	58,928	75,392	102,209	168,000
Allens Creek	104,860	132,928	169,785	202,310	252,197
Total system reservoirs	**831,782**	**1,020,653**	**1,229,572**	**1,534,310**	**2,269,434**



Reservoirs

BWAM_ID	RESERVOIR ID	Name
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515831	AQUILA	Lake Aquilla
509431	LKWACO	Lake Waco
515931	PRCTOR	Lake Proctor
516031	BELTON	Lake Belton
516131	STLHSE	Lake Stillhouse Hollow
516231	GRGTWN	Lake Georgetown
516331	GRNGER	Lake Granger
516431	SMRVLE	Lake Somerville
516531	LMSTNE	Lake Limestone
292531	ALLENS	Allens Creek

Gaging Stations

BWAM_ID	Stream	Near_City
BRDE29	Brazos	Dennis
BRGR30	Brazos	Glen Rose
BRWA41	Brazos	Waco
BRHB42	Brazos	Highbank
LEHM46	Leon	Hamilton
LEGT47	Leon	Gatesville
LRCA58	Little	Cameron
BRBR59	Brazos	Bryan
NABR67	Navasota	Bryan
BRHE68	Brazos	Hempstead
BRRI70	Brazos	Richmond
BRGM73	Brazos	Gulf of Mexico

FIGURE 4.2 Brazos River Basin subbasins.

TABLE 4.4 Yield-Reliability for Individual Reservoirs, Without Including Allens Creek

Reservoir	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Possum kingdom	333,300	384,896	411,860	455,200	545,000
Lake Granbury	70,855	96,965	119,785	145,534	220,500
Lake Whitney	12,700	31,892	63,178	112,400	224,500
Lake Proctor	21,135	23,724	27,965	35,430	52,081
Lake Belton	115,560	128,407	159,421	203,295	324,150
Lake Stillhouse Hollow	63,380	69,965	90,896	117,600	176,500
Lake Georgetown	11,527	13,741	17,302	22,311	36,750
Lake Granger	19,000	23,302	30,948	44,649	85,000
Lake Aquilla	14,280	19,777	25,753	33,515	55,860
Lake Waco	93,120	106,928	123,785	160,209	242,325
Lake Limestone	66,770	81,928	98,896	134,600	208,000
Lake Somerville	43,470	58,928	75,392	102,209	168,000
Total system reservoirs	**750,842**	**909,801**	**1,093,431**	**1,371,313**	**2,044,260**

If all system reservoirs firm yields are added up, a total firm yield of 831,782 ac-ft/yr is obtained if Allens Creek reservoir is included, while 750,842 ac-ft/yr is obtained if Allens Creek reservoir is not included. Again, this is the firm yield (100% period and volume reliability) that could be obtained if all reservoirs are operated individually.

If the Texas Commission on Environmental Quality (TCEQ) is willing to approve a permit with a period reliability less than 100% and backed up by groundwater or water from another source the remaining of the time, reservoir yields could be increased by the percents shown in Tables 4.5 and 4.6.

In the scenario with Allens Creek reservoir, and with a period reliability of 98%, Possum Kingdom could increase its yield by 63,600 ac-ft/yr (21%) and the total yield of the reservoirs included in the system could be increased by 188,000 ac-ft/yr (23%).

In the scenario without Allens Creek, the total system yield could be increased by 159,000 ac-ft/yr (21%). These increases are very significant, since most reservoirs' firm yields are less than this amount. This translates into savings of millions of dollars in new infrastructure.

By constructing Allens Creek reservoir, an increment of the total yield of 80,000 ac-ft/yr can be achieved, if reservoirs are operated individually.

TABLE 4.5 Yield Increase for a Period Reliability Different than 100%, With Allens Creek

Reservoir	Yield increase for different period reliabilities (%)				
	100%	98%	95%	90%	75%
Possum kingdom	-	21	30	42	72
Lake Granbury	-	27	58	96	199
Lake Whitney	-	134	284	694	1736
Lake Proctor	-	12	32	68	146
Lake Belton	-	11	38	76	180
Lake Stillhouse Hollow	-	10	43	86	178
Lake Georgetown	-	19	50	94	219
Lake Granger	-	23	63	135	344
Lake Aquilla	-	38	80	135	291
Lake Waco	-	15	33	72	160
Lake Limestone	-	23	48	100	210
Lake Somerville	-	36	73	135	286
Allens Creek	-	27	62	93	141
Total system	-	23	48	84	173

TABLE 4.6 Yield Increase for a Period Reliability Different than 100%, Without Allens Creek

Reservoir	Yield increase for different period reliabilities (%)				
	100%	98%	95%	90%	75%
Possum kingdom	-	15	24	37	64
Lake Granbury	-	37	69	105	211
Lake Whitney	-	151	397	785	1668
Lake Proctor	-	12	32	68	146
Lake Belton	-	11	38	76	181
Lake Stillhouse Hollow	-	10	43	86	178
Lake Georgetown	-	19	50	94	219
Lake Granger	-	23	63	135	347
Lake Aquilla	-	38	80	135	291
Lake Waco	-	15	33	72	160
Lake Limestone	-	23	48	102	212
Lake Somerville	-	36	73	135	286
Total system	-	21	46	83	172

4.2 YIELD-RELIABILITY TABLES FOR SYSTEM DIVERSION AT CAMERON, GLEN ROSE, HIGH BANKS, AND GULF USING SIMPLIFIED DATASET

The purpose of this approach is to calculate the available yield at four different locations (Glen Rose, High Bank and Gulf of Mexico on the Brazos River and Cameron Gage at the Little Brazos River) with upstream reservoirs working as a system. In addition to the two previous scenarios (with or without Allens Creek reservoir) two new scenarios are included. The first one allows the use of unregulated (unappropriated) flows at the diversion location, and the second one doesn't.

Where applicable, Proctor and Waco reservoirs divert their firm yields, calculated in section 4.1, and are senior to any other water right. The total capacity of each reservoir was used to make diversions, with the exception of Lake Belton, where 5,000 ac-ft were defined as inactive storage, in order to protect a local right for Fort Hood. All reservoirs have only one depleting zone, corresponding to 100% of the storage capacity.

The modeling process is the following:

- All water rights are removed from the simplified dataset.
- Non system reservoirs are senior and deplete their individual reservoir firm yield.
- System reservoirs refill storage, upstream reservoirs are senior to downstream reservoirs.
- The system diversion is made at the specified location, only reservoirs located upstream of the diversion location are considered in the simulation.
- System reservoirs refill storage at the same relative priorities.

4.2.1 Yields including unregulated flows

In this case, in addition to reservoir releases to the diversion location, the water right also uses unregulated flows. These unregulated flows are unappropriated flows after all the other water rights in the basin have made their diversions.

After running one simulation per diversion location and for each scenario, Tables 4.7 and 4.8 show the different yields obtained.

TABLE 4.7 Yield-Reliability Using System Diversion, Including Allens Creek Reservoir, Using Unappropriated Flows

Diversion location	Period Reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Cameron gage	214,300	240,344	304,357	453,800	734,000
Glen Rose	380,340	465,785	546,357	615,166	746,208
High Banks	533,460	599,827	758,928	1,001,551	1,363,372
Gulf	1,176,190	1,443,928	1,906,785	2,429,000	3,646,315

TABLE 4.8 Yield-Reliability Using System Diversion, Without Allens Creek Reservoir, Using Unappropriated Flows

Diversion location	Period Reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Cameron gage	218,000	243,929	311,586	457,241	748,982
Glen Rose	414,070	499,785	577,357	643,379	770,000
High Banks	582,620	639,642	823,928	1,063,000	1,063,000
Gulf	1,085,850	1,323,928	1,831,785	2,339,000	3,470,000

The system diversion at the Gulf of Mexico increases if Allens Creek reservoir is constructed, this is because Allens Creek is located near the diversion location and captures unappropriated flows from wet months and later makes releases when needed.

The diversion at the Gulf of Mexico is the only one that increases when considering Allens Creek reservoir. All other 3 diversions decrease after this reservoir is constructed. Additional runs of the simplified dataset, as well as the complete dataset, show that if Allens Creek is not considered, unappropriated flows increase at other locations, like Possum Kingdom, Granbury, Whitney and others; increasing the water available to those rights. Figure 4.3 shows the increase in unappropriated flows in Possum Kingdom if Allens creek is removed from the simulation. Later on in the system simulation, Possum Kingdom is going to have access to those additional unappropriated flows, increasing its yield. A similar situation occurs for other reservoirs.

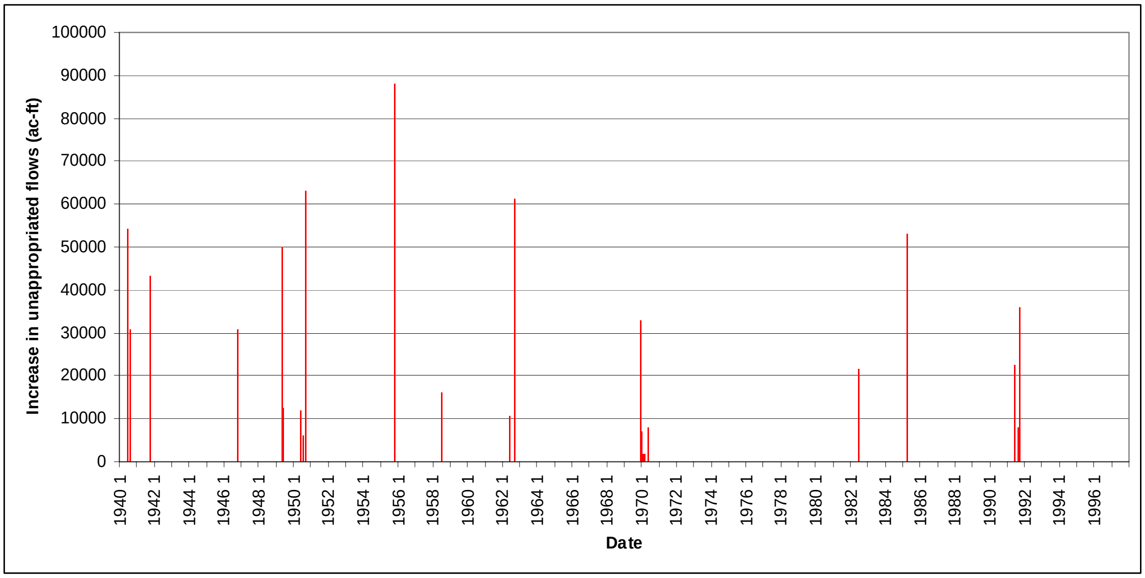


FIGURE 4.3 Increase in unappropriated flows at Possum Kingdom if Allens Creek reservoir is removed from the simulation.

4.2.2 Yields not including unregulated flows

This condition was only evaluated for diversions at Cameron gage and at the Gulf of Mexico. With this condition, diversions only have access to reservoir releases (water right type 3). Under these conditions, the results obtained are shown in Tables 4.9 and 4.10.

TABLE 4.9 Yield-Reliability Using System Diversions Type 3, With Allens Creek Reservoir

Diversion location	Period Reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Cameron gage	205,900	229,785	291,178	417,800	633,500
Gulf	952,070	1,104,482	1,410,892	1,773,023	2,414,883

TABLE 4.10 Yield-Reliability Using System Diversions Type 3, Without Allens Creek Reservoir

Diversion location	Period Reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Cameron gage	205,900	229,209	289,571	417,241	640,000
Gulf	830,390	929,285	1,197,857	1,513,103	2,065,000

As expected, the diversion at the Gulf of Mexico for the simulation including Allens Creek reservoir has a higher firm yield, than the one without it, while at Cameron gage, the firm yield showed no change. The increase in the firm yield at the Gulf of Mexico, when considering Allens Creek reservoir is greater when there is no access to unappropriated flows than when there is. In the first case, an increase of 122,000 ac-ft/yr is reached, while in the second case the increase is only 90,000 ac-ft/yr.

When comparing these firm yields with the ones obtained with single reservoirs, it is noticed that having a system of reservoirs instead of single reservoirs, produces a higher yield. Table 4.11 summarizes the results.

TABLE 4.11 Summary of Results, Yield at the Gulf of Mexico

	Without Allens Creek Firm yield (ac-ft/yr)	With Allens Creek Firm yield (ac-ft/yr)
Individual Reservoirs	**750,842**	**831,782**
System reservoirs type 3	**830,390**	**952,070**
System reservoirs type 2	**1,085,850**	**1,176,190**

In all cases, if a system of reservoirs is used instead of individual reservoirs, the yield increases, if Allens Creek reservoir is not considered, an increase of 11% (79,500 ac-ft/yr) is achieved just by working as a system and not having access to unappropriated flows, while an increase of 45% (335,000 ac-ft/yr) is obtained if in addition to working as a system, the diversion at the gulf has access to unappropriated flows.

If Allens Creek reservoir is considered, an increase of 14% (121,000 ac-ft/yr) is achieved if reservoirs are operated as a system and the diversion location has no access to unappropriated flows. An increase of 41% is accomplished if in addition to the system, diversions have access to unappropriated flows.

These increases in yields are significant, if no reservoir system operations were allowed, a similar increase in yield would require the construction of several reservoirs. For example, if Allens Creek is not constructed, the firm yield for individual reservoirs is 750,842 ac-ft/yr ; if existing reservoirs are operated as a system, and no unappropriated streamflow depletions are allowed, the yield is increased to 830,390 ac-ft/yr, which is the same yield that would be achieved if Allens Creek reservoir is built and no reservoir system operations are allowed.

4.3 SINGLE RESERVOIR YIELD-RELIABILITY FOR ALL BRA SYSTEM RESERVOIRS USING PRIORITY OPTION (MFY=2 ON FY RECORD) WITH LIMITS SET AT WATER RIGHTS

The purpose of this approach is to calculate a yield-reliability table, by using a new option in the FY record, called MFY=2, which based on the priorities from each WR record, assigns the yield to the most senior priority right up to the WR record field 3 diversion amount. Any yield remaining is assigned to the right with the next most senior priority up to its WR record field 3 diversion amount, and so forth. If any yield remains, it is assigned to the most junior right, regardless of its diversion target.

This analysis was performed on both, the full dataset and the simplified dataset (including Allens Creek reservoir), obtaining on both simulations the same firm yield, 406,200 ac-ft/yr. This yield is almost half of the firm yield that was obtained using individual reservoirs, without using the priority option. This could be explained because of the existence of rights with diversion amounts that exceed the individual reservoir firm yield. Table 4.12 compares both amounts, notice that rights at reservoirs Whitney, Stillhouse Hollow, Georgetown, Granger and Somerville exceed the Firm Yield amount.

Stillhouse Hollow is the most senior of these reservoirs, when evaluating the results of the simulations, it was found that Stillhouse Hollow’s rights were the last rights to make depletions; junior rights finished the simulation without being assigned any diversion amount.

The yield-reliability for each simulation is shown in Figures 4.4 and 4.5. Notice that the results are almost identical between the simplified dataset and the full dataset, which again demonstrates the reliability of the simplified dataset.

Observe that the period reliability obtained is not 100%, this is because a yield is considered a firm yield, when the mean annual shortage is less than 0.05 ac-ft. In this simulation there are around 100 rights, some of them with very small targets. It is possible that these small target rights incur in shortage, a very small shortage. Since these shortages are so small, they will not affect the firm yield, but the period reliability is affected, since it doesn't consider the magnitude of the shortage, only the shortage itself.

TABLE 4.12 Individual Reservoirs Firm Yield and Permitted Diversions

Reservoir	Firm Yield (ac-ft/yr)	Permitted diversions (ac-ft/yr)
Possum Kingdom	310,180	230,750
Lake Granbury	70,855	64,712
Lake Whitney	11,900	18,336
Lake Proctor	21,135	19,658
Lake Belton	115,560	112,257
Lake Stillhouse Hollow	63,380	67,768
Lake Georgetown	11,527	13,610
Lake Granger	19,000	19,840
Lake Aquilla	14,280	13,896
Lake Waco	93,100	79,869
Lake Limestone	66,770	65,074
Lake Somerville	43,470	48,000
Allens Creek	104,860	99,650

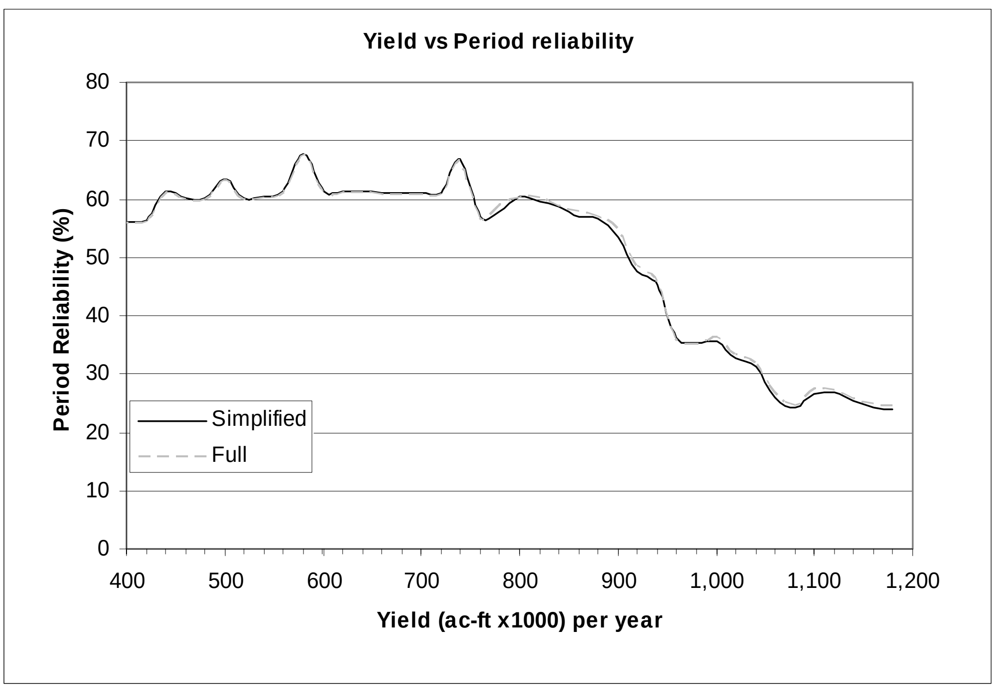


FIGURE 4.4 Yield-period reliability using priority option on FY record.

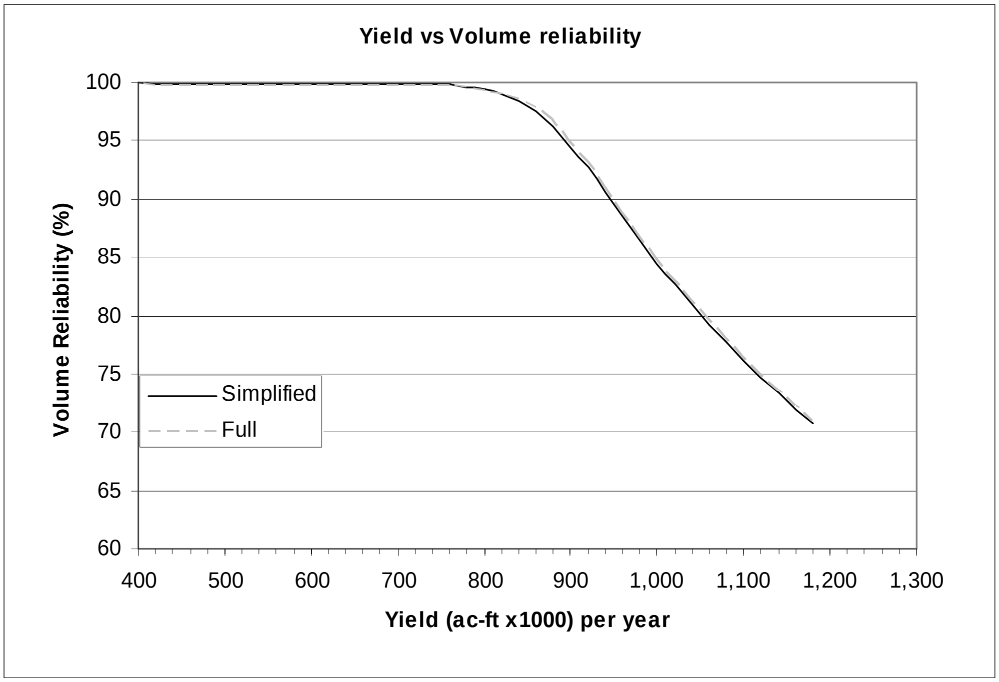


FIGURE 4.5 Yield-volume reliability using priority option on FY record.

In order to analyze this event, different stopping criterions were used with the same dataset, obtaining the results shown in Figure 4.6. Notice the significant difference between a stopping criterion of 0.05 (default) and 0.005, the firm yield is reduced half. While for some stopping criterion, the firm yield remains the same or very similar, between a stopping criterion of 0.03 and 0.017, the firm yield has its greatest decrease, from 402,000 ac-ft/yr to 227,000 ac-ft/yr. In the same interval, period reliabilities increased from around 50% to 100%.

If it is desired to have a period reliability of 100% for the firm yield, then the adequate stopping criteria would be an average annual shortage of 0.019 ac-ft and the correspondent firm yield would be 292,000 ac-ft/yr.

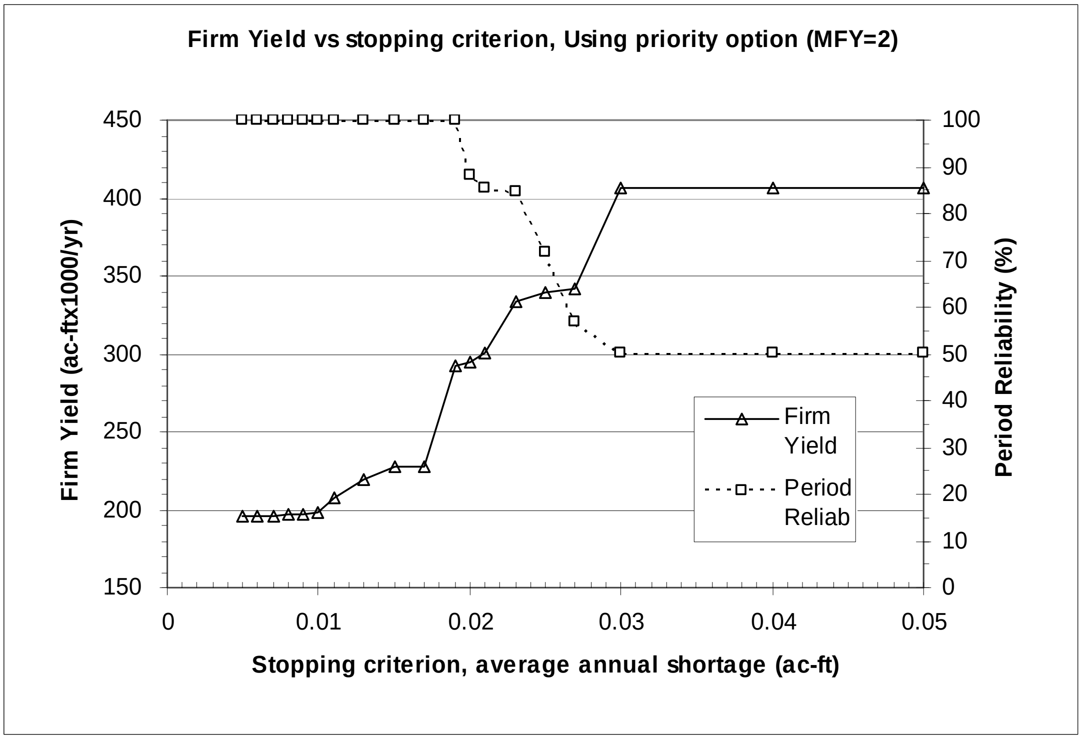


FIGURE 4.6 Variation of firm yield with stopping criterion, using priority option, MFY=2.

4.4 YIELD-RELIABILITY ANALYSIS FOR SYSTEM DIVERSION AT GULF EXCLUDING UNREGULATED FLOWS, USING THE DUAL OPTION AND THE SIMPLIFIED DATASET APPROACHES

The objective of this approach is to compare the results obtained by using the simplified dataset and the dual simulation option. The dual simulation option is a new feature in WRAP that performs automatically two simulations. The first one computes streamflow depletions under specified conditions for selected rights. The streamflow depletions computed during the initial simulation, are used as upper limits to constrain streamflow depletions, during the second simulation. The dual simulation option was added primarily for situations where multiple water rights with different priority are associated with the same reservoirs. In the case of issuing a new right permit, this right would be junior to all existing rights and should not affect reliabilities on any other rights in the basin. But since it is receiving water from a reservoir that has other senior rights, the new right will decrease the storage level at a junior priority, but storage will be refilled at the most senior priority of the rights located at the reservoir, so other rights in the basin are affected by the new right.

The dual option would take care of this situation, by performing an initial simulation without including the new right, and developing an array of streamflow depletions for the senior rights that refill storage at that reservoir. These initial streamflow depletions become limits on the amount of water available to these rights during the second simulation, when the new right is included.

The dual option was applied on the complete dataset, including all the more than 3000 control points. Two scenarios were considered, the first one including Allens Creek reservoir, and the second one without including it. The procedure followed to apply the dual option is the following:

- All the original rights that receive water from any of the BRA reservoirs included in the system must be constrained in the second simulation. So these rights use option 4 of the dual option.
- Following each one of the original rights that were modified in the previous step, a new right with the same priority, but with a zero diversion target and an option 5 on the dual option was created. This option constrains the streamflow depletions on the new right by the streamflow depletions made by the preceding right (original right) in the dataset.
- A new system diversion right at the Gulf of Mexico was created; this right is junior to all other water rights in the basin. This right is only activated during the second simulation, so it uses option 2 of the dual option. Since the use of unregulated flows is not allowed, this is a type 3 right.
- System reservoirs refill storage with their same relative priorities. These rights are also activated only during the second simulation.

The simplified dataset includes all BRA system reservoir rights and also includes rights from Proctor and Waco reservoirs. The procedure followed to set up the simulation is the following:

- All BRA system reservoir rights target are set to zero, so they only refill storage. Non system rights (Waco and Proctor) remain the same, so they deplete and refill storage at their original priorities.
- The system diversion is made at the Gulf of Mexico, using all the reservoirs included in the system.
- System reservoirs refill storage at the same relative priorities.

Results of the different simulations are shown in the following sections.

4.4.1 With Allens Creek reservoir

A firm yield of 979,670 ac-ft/yr was obtained using the dual simulation option and 951,950 ac-ft/yr were obtained when using the simplified approach. This is a difference of almost 3%. This discrepancy can be explained by differences when balancing reservoirs storage, as described ahead. Table 4.13 shows the Yield-Period reliability table obtained for both approaches.

TABLE 4.13 Yield-Period Reliability for Simplified and Dual Approaches, With Allens Creek

Modeling approach	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Simplified dataset	951,950	1,109,655	1,387,857	1,761,551	2,420,000
Dual option	979,670	1,132,727	1,498,604	1,730,422	2,247,478

Figure 4.7 shows Yield-Period reliability for the dual and simplified dataset approaches. For higher yields, the simplified dataset approach gives a higher period reliability than the dual option, but at some point, near a reliability of 91%, the dual option starts giving higher reliabilities than the simplified dataset. Although the final result is very similar for both approaches.

Figure 4.8 shows Yield-Volume reliability for the dual and simplified dataset approaches. Similarly to the Yield-Period reliability results, volume reliabilities for the simplified dataset are higher for higher yields, while for small yields the dual option reliabilities are slightly higher.

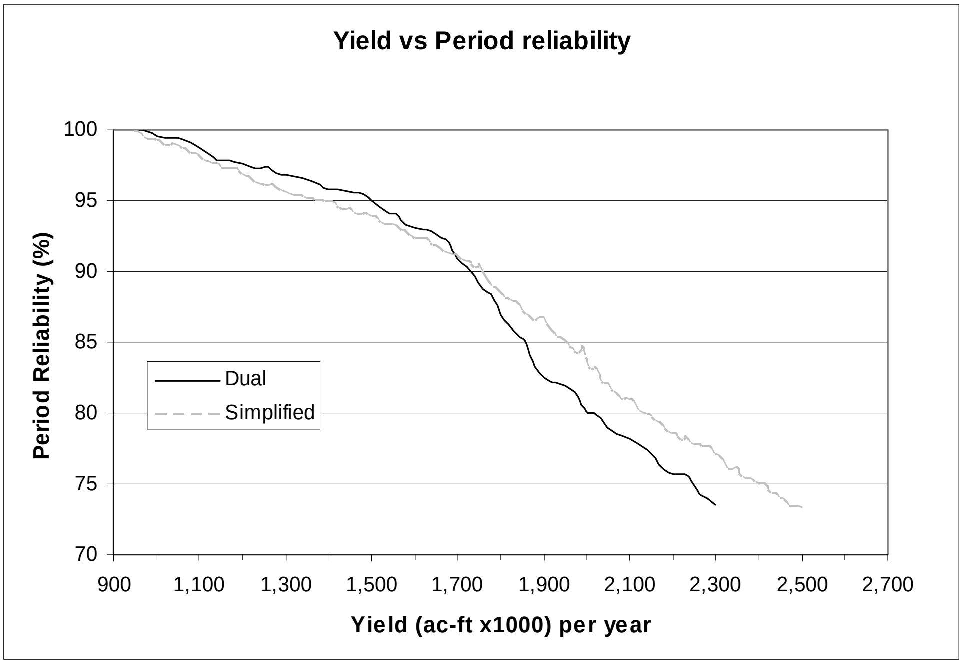


FIGURE 4.7 Yield-period reliability, diversion at the Gulf of Mexico without having access to unappropriated flows, using dual and simplified dataset approaches, including Allens Creek reservoir.

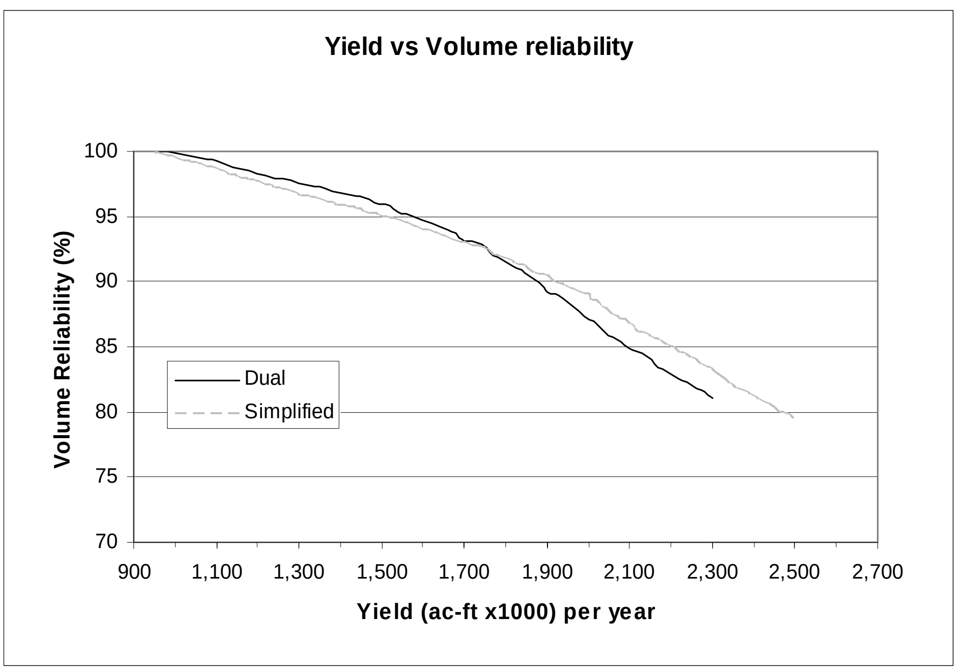


FIGURE 4.8 Yield-volume reliability, diversion at the Gulf of Mexico without having access to unappropriated flows, using dual and simplified dataset approaches, including Allens Creek reservoir.

Multiple reservoir system operations are based on balancing reservoir storage, and this balance is based on computing a ranking index for each reservoir in the system, with the release that month being made from the reservoir with the greatest index. The index is computed as

$$Rank\,index = M\left(\frac{Content}{Capacity}\right) + A$$

Where M and A are defined in the OR record.

The Dual simulation does not allow specified rights to deplete more water than the amounts depleted during the initial simulation. During the initial simulation, targets for these rights were the original permitted amounts, while during the second simulation these targets were modified to only refilling storage rights. Additional water, if any, (water that was used to meet targets during the initial simulation) may have been used by non system rights, but in any case not by system rights.

By default, the simplified dataset considers streamflow depletions and unappropriated flows at selected locations made during the complete simulation (same initial simulation of the dual option). During the complete simulation those rights had a diversion target different than zero, so they were refilling storage as well as meeting that target. Now, when using the simplified dataset to model a system of reservoirs, rights first refill storage, then releases are made to the diversion location and finally all system reservoirs refill storage. Available water is constrained by the “naturalized flows”, but no limits are set within the dataset. Since at the beginning of the simulation, rights are only refilling storage, there is additional water that is not being used, (water that was used to meet targets during the complete simulation) and now this water is available to junior rights that during the complete simulation had no water available to meet their needs. Therefore, these junior rights will increase their storage. For example, if Possum Kingdom reservoir is full, rights at that location will only replace water lost by evaporation, and water that was depleted during the complete simulation to meet demands different than storage, will be available to any other junior right (almost every other reservoir) that didn’t meet its demands or its reservoir is not full.

Rounding errors when creating the new evaporation depths file can make a big difference when calculating ranking indexes.

Because of these reasons, reservoirs performing releases a specific month of the simulation are different between the dual and simplified approaches; this can modify the final results and explain the 3% of difference in firm yields between the two approaches.

4.4.2 Without Allens Creek reservoir

In this scenario, a firm yield of 836,320 ac-ft/yr was obtained using the dual option, while 830,050 ac-ft/yr were obtained using the simplified dataset approach. In this case the difference is less than 0.5%, but the same reasons explained in the previous section apply to this one. Table 4.14 shows the Yield-Period Reliability table obtained for both approaches.

Figure 4.9 shows the Yield-Period reliability results obtained for the dual option and the simplified simulation. Differences in reliabilities are higher for higher yields, but after a yield of 1,400,000 ac-ft/yr, reliabilities for both approaches are very similar.

TABLE 4.14 Yield-Period Reliability for Simplified and Dual Approaches, Without Allens Creek

Modeling approach	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Simplified dataset	830,050	924,482	1,187,857	1,506,046	2,061,971
Dual option	836,320	944,561	1,205,116	1,432,093	1,886,511

Figure 4.10 shows the Yield-Volume reliability results obtained for both, dual and simplified dataset approaches. Like in previous analysis higher yields produce greater differences, but from a certain point in the simulation, these differences decrease until they are almost negligible.

As expected, the firm yield is higher by 14% when considering the scenario including Allens Creek reservoir.

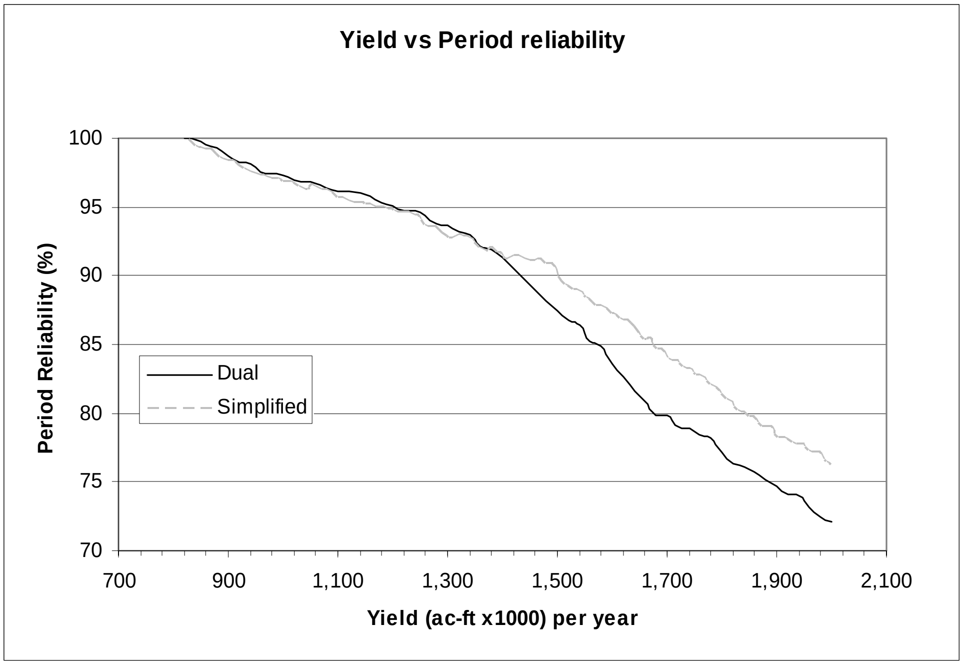


FIGURE 4.9 Yield-period reliability, diversion at the Gulf of Mexico without having access to unappropriated flows, using dual and simplified dataset approaches, without including Allens Creek reservoir.

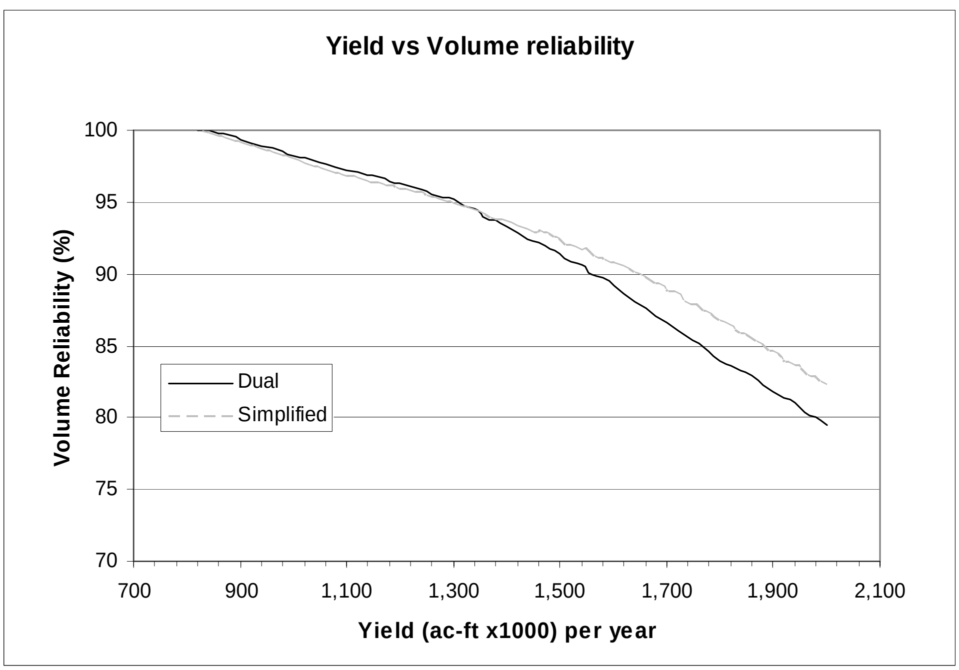


FIGURE 4.10 Yield-volume reliability, diversion at the Gulf of Mexico without having access to unappropriated flows, using dual and simplified dataset approaches, without including Allens Creek reservoir.

4.5 YIELD-RELIABILITY ANALYSIS FOR SYSTEM DIVERSION AT GULF INCLUDING UNREGULATED FLOWS, USING THE DUAL OPTION AND THE SIMPLIFIED DATASET APPROACHES

The procedure and methodologies followed in this approach are very similar to the one used in section 4.4 and is described in that section. The only difference is that the system diversion at the Gulf of Mexico uses unregulated flows (type 2 right). Results obtained for the different scenarios are shown in the following sections.

4.5.1 With Allens Creek reservoir

A firm yield of 1,171,160 ac-ft/yr was obtained using the simplified dataset approach, and 1,159,240 ac-ft/yr was obtained using the dual simulation option. This gives a difference of approximately 1% between both approaches. The same reasons explained in section 4.5.1 apply to this section and the following one. Yield-Reliability table is shown in Table 4.15.

TABLE 4.15 Yield-Period Reliability for Simplified and Dual Approaches, With Allens Creek

Modeling approach	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Simplified dataset	1,171,160	1,439,310	1,912,093	2,455,862	3,639,247
Dual option	1,159,240	1,448,965	1,835,714	2,304,186	3,360,000

Figure 4.11 shows Yield-Period reliability results obtained for the dual simulation and simplified dataset approaches; Figure 4.12 shows the results obtained for yield-Volume reliability. Again as seen before, higher yields have greater differences in reliability than lower yields, at yield of approximately 2,100,000 ac-ft/yr, reliabilities are about the same.

Compared to the results obtained in section 4.4.1 (system diversion at the Gulf without access to unappropriated flows), when having access to unappropriated flows, firm yields increase in about 20%.

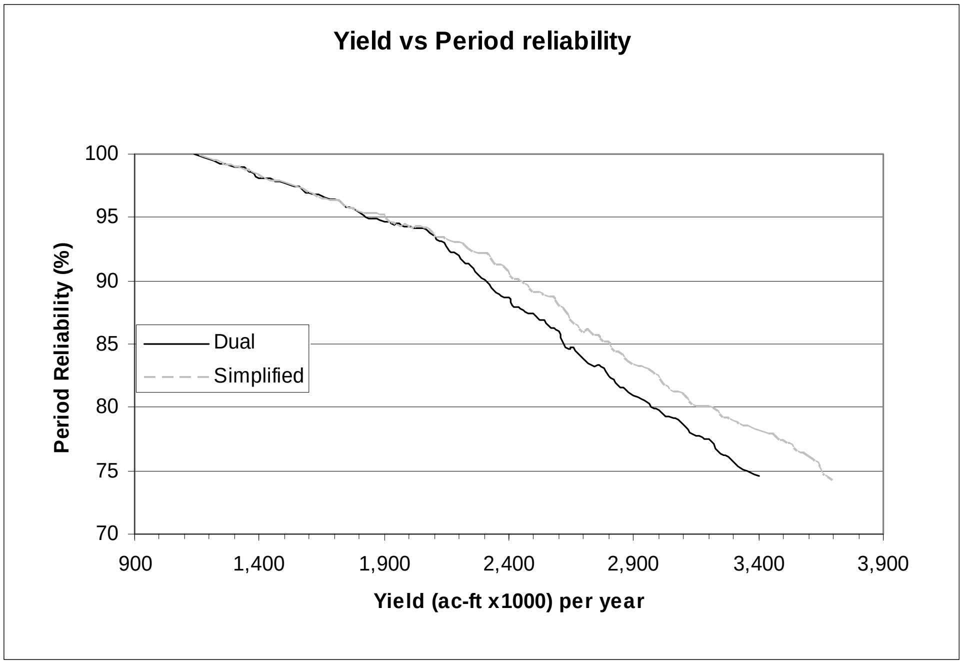


FIGURE 4.11 Yield-period reliability, diversion at the Gulf of Mexico having access to unappropriated flows, using dual and simplified dataset approaches, including Allens Creek reservoir.

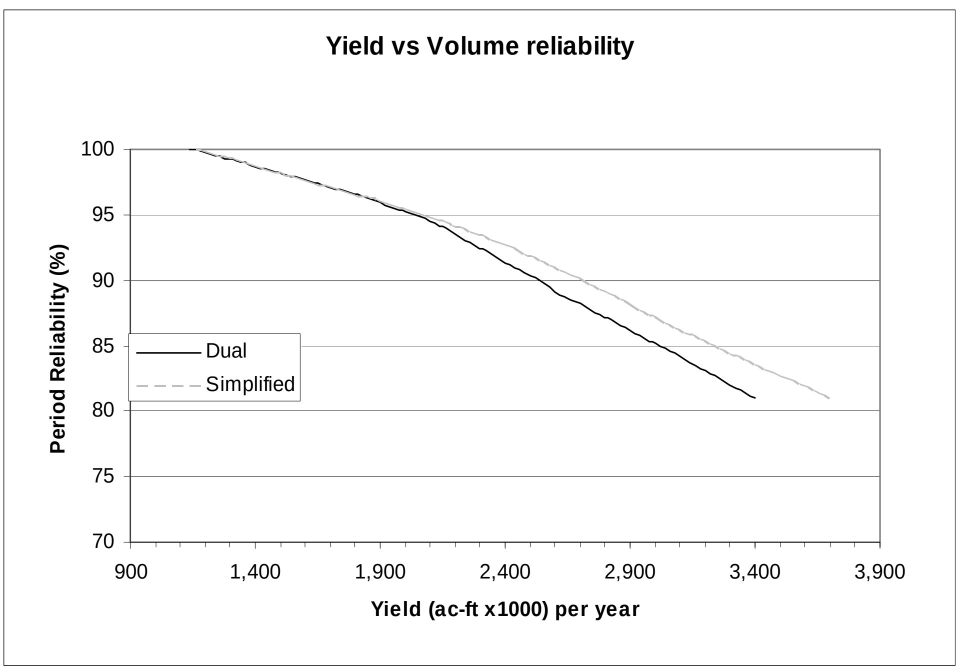


FIGURE 4.12 Yield-volume reliability, diversion at the Gulf of Mexico having access to unappropriated flows, using dual and simplified dataset approaches, including Allens Creek reservoir.

4.5.2 Without Allens Creek reservoir

A firm yield of 1,081,640 ac-ft/yr was obtained using the simplified dataset approach, and 1,064,720 ac-ft/yr was obtained using the dual simulation option. This gives a difference of approximately 1.5% between both approaches. Yield-Reliability table is shown in Table 4.16.

TABLE 4.16 Yield-Period Reliability for Simplified and Dual Approaches, Without Allens Creek

Modeling approach	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Simplified dataset	1,081,640	1,319,534	1,827,857	2,338,333	3,473,488
Dual option	1,064,720	1,319,310	1,788,965	2,190,697	3,176,056

Figure 4.13 shows yield-Period reliability results obtained for the dual simulation and simplified dataset approaches; Figure 4.14 shows the results obtained for yield-Volume reliability. Again as seen before, higher yields have greater differences in reliability than lower yields, at yield of approximately 1,800,000 ac-ft/yr, reliabilities are about the same.

When comparing the firm yield obtained under these conditions with the one obtained in section 4.4.2 (no access to unappropriated flows, no Allens Creek reservoir), the firm yield when having access to unappropriated flows increase by 30%.

If access to unappropriated flows is allowed, the inclusion of Allens Creek reservoir results in an increase of 8% in the firm yield.

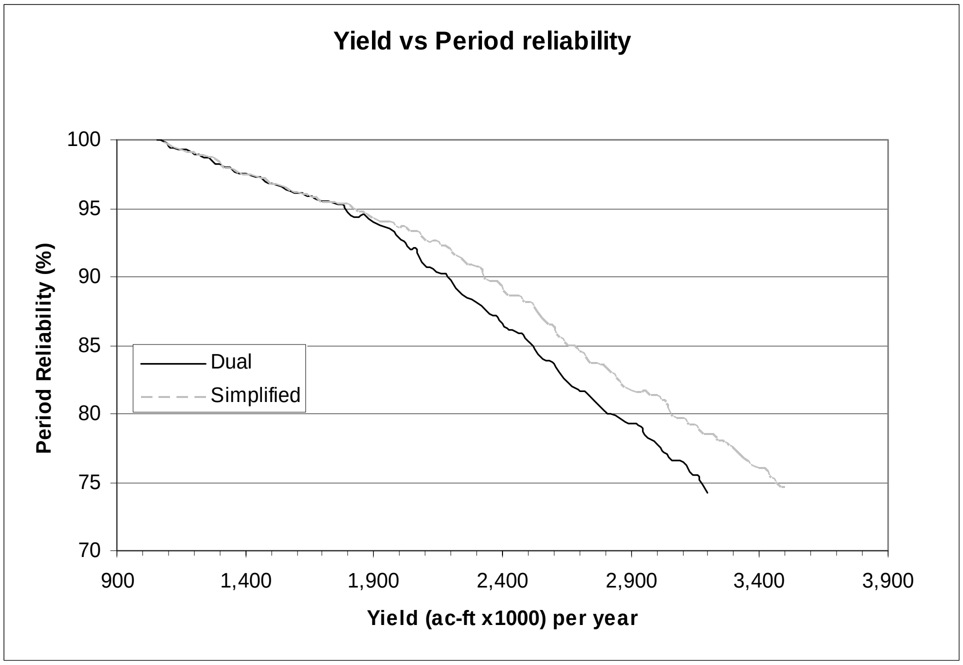


FIGURE 4.13 Yield-period reliability, diversion at the Gulf of Mexico having access to unappropriated flows, using dual and simplified dataset approaches, without Allens Creek reservoir.

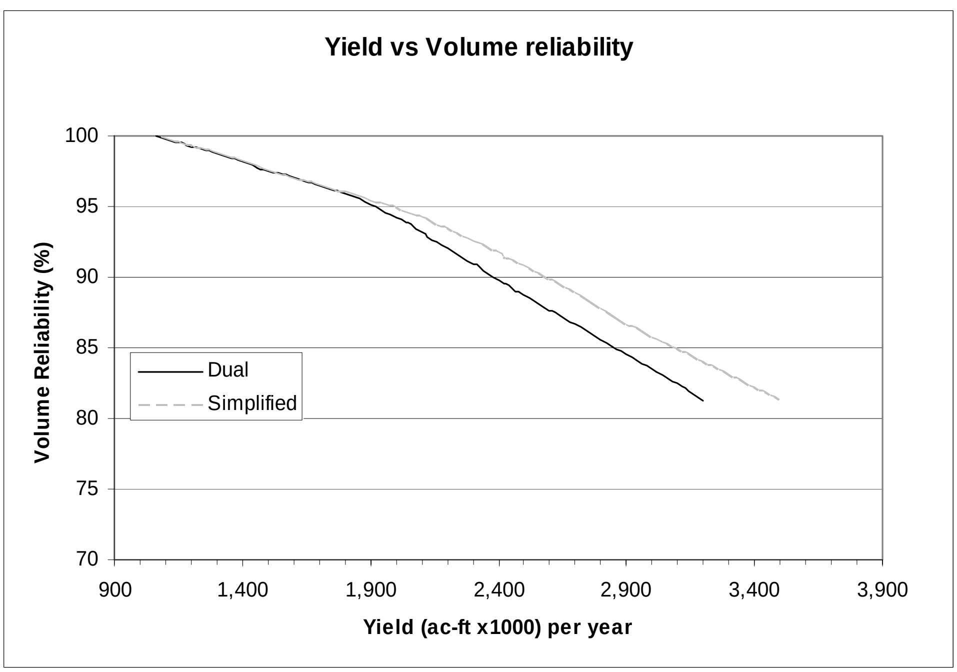


FIGURE 4.14 Yield-volume reliability, diversion at the Gulf of Mexico having access to unappropriated flows, using dual and simplified dataset approaches, without Allens Creek reservoir.

4.6 REPRODUCTION OF BRA SYSTEM PERMIT FIRM YIELDS AT THE GULF OF MEXICO

The objective of this section is to reproduce the results obtained by the BRA for their system permit application at the Gulf of Mexico, by using the dual simulation option.

4.6.1 Freese and Nichols/Espey Approach

An approach used by Freese and Nichols/Espey in a recent study for the BRA is based on running two different simulations, the first one is the original TCEQ WAM dataset that is used to extract the amount of water depleted by each one of the BRA rights. In the second simulation, all original BRA rights were removed, and new rights are created, (one right per control point) with a target amount defined by target series records containing the amounts of water depleted in the initial simulation (at each control point). These rights have the same priority date as the original rights. Water depleted by this rights, instead of refilling storage at the reservoir, is sent to dummy control points created for each BRA system reservoir.

After all non-BRA water rights have diverted, BRA reservoirs are refilled with the water stored in the dummy control points, any water remaining in the dummy control points is returned to the stream at the original point of diversion. Instream flows requirements are activated at the Richmond gage, following the Lyons method. Later, reservoirs refill storage with any unappropriated flows and water released from dummy control points.

The system diversion is made at the Gulf of Mexico, for all BRA system reservoirs, the total storage capacity is divided into 2 zones to balance the storage among reservoirs. In all cases, Zone 1 (first being depleted) is 70% of the reservoir capacity and zone 2 is 30%. After the system diversion has been made, all reservoirs refill storage with any remaining unappropriated flows.

This approach is similar to what the dual simulation option does, except, the dual simulation works with individual water rights instead of lumping several water rights located at the same control point into a single right, and the dual simulation doesn’t use dummy control points, it directly refills storage with depletions made from the river.

The dataset used to perform this analysis is slightly different that the one used previously, Proctor reservoir is considered part of the system and some modeling premises were changed. The firm yield found using this approach was 1,183,400 ac-ft/yr. Yield-reliability is shown in Table 4.17.

TABLE 4.17 Yield-Period Reliability for System Diversion at the Gulf, Using F&N/ESPEY Approach

Modeling approach	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
F&N/ESPEY	1,183,400	1,474,137	1,944,827	2,453,461	3,607,000

4.6.2 Dual simulation option approach

The procedure used to apply the dual simulation is described here:

- All the original rights that receive water from any of the BRA reservoirs included in the system, must be constrained in the second simulation. So these rights use option 4 of the dual option.
- Following each one of the original rights that were modified in the previous step, a new right with the same priority, but with a zero diversion target and an option 5 on the dual option was created. This option constrains the streamflow depletions on the new right by the streamflow depletions made by the preceding right (original right).
- After all the existing rights have being modeled, the new instream flow requirement at the Richmond gage is activated using dual option 2.
- System reservoirs refill storage with unappropriated flows and water that was not used by BRA rights but that was depleted during the initial simulation.
- A new system diversion right at the Gulf of Mexico is created; this right is junior to all other water rights in the basin. This right is only activated during the second simulation, so it uses option 2 of the dual option. Since the use of unregulated flows is allowed, this is a type 2 right.
- System reservoirs refill storage with their same relative priorities. These rights are also activated only during the second simulation.

The resulting firm yield is 1,188,100 ac-ft/yr, which is very similar to the one obtained using Freese and Nichols/ ESPEY approach. Table 4.18 shows the yield-period reliability results obtained.

TABLE 4.18 Yield-Period Reliability for System Diversion at the Gulf Using the Dual Option

Modeling approach	Yields vs period reliability (volumes in ac-ft)				
	100%	98%	95%	90%	75%
Dual option	1,188,100	1,474,137	1,885,087	2,388,372	3,429,861

Figure 4.15 shows the Yield-Period reliability results obtained for both approaches, notice that both methodologies produce similar results. Figure 4.16 shows the results obtained for yield-volume reliability, using both approaches. The values obtained are very similar.

The results show that both approaches give basically the same firm yield and similar values for intermediate yields. So either approach can be used, being the dual option the easiest one to apply, since it does not involve the creation of Target Series records, nor dummy control points

4.7 INTERRUPTIBLE YIELDS

As described in sections 4.1 to 4.5, firm yields were calculated for individual reservoirs and reservoirs operated as a system. It was shown that a system gives a higher firm yield than individual reservoirs. Interruptible yields, as its name describes, are yields that do not have a reliability of 100%, so they are not always available.

These yields may not be proper to meet needs that require a reliability of 100%, but may be suitable for irrigation or other purposes that do not require a reliability of 100%. TCEQ requires irrigation rights to meet 75% of the target 75% of the time.

Interruptible yields may represent a considerable increase in the amount of water that may be sold to farmers and other clients that may not need water 100% of the time. In order to increase these interruptible yields, the firm yield can be decreased by a certain amount, so that the amount that was taken from the firm yield can be distributed over time with a non 100% reliability.

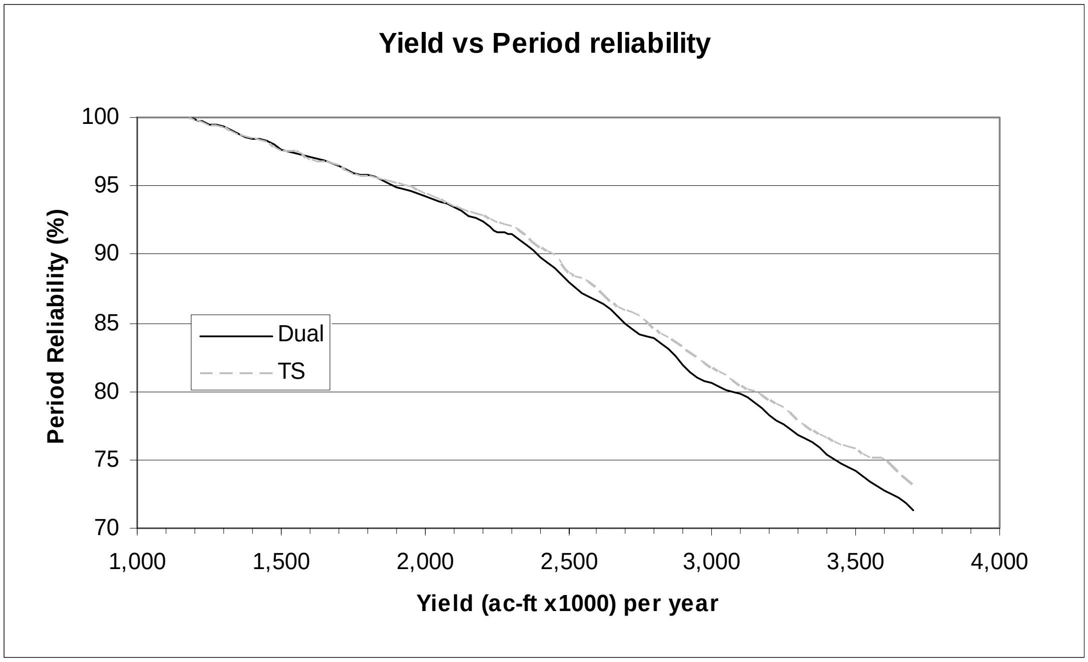


FIGURE 4.15 Yield-period reliability results for diversion at the Gulf, using dual option and target series (F&N/ESPEY).

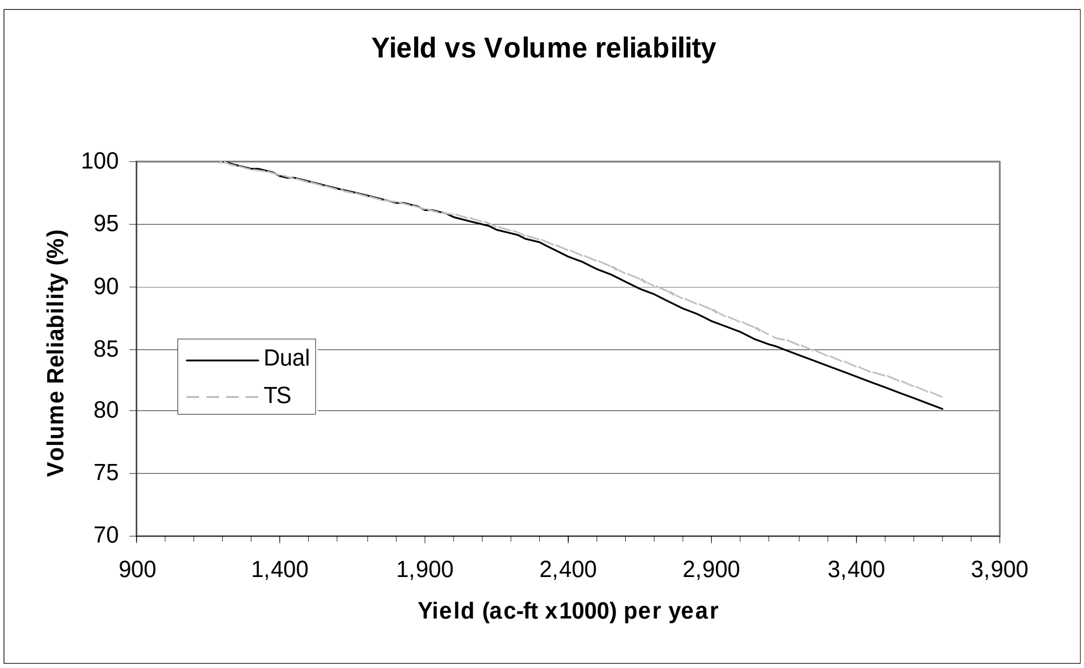


FIGURE 4.16 Yield-volume reliability results for diversion at the Gulf, using dual option and target series (F&N/ESPEY).

In addition to the percent of reduction in the firm yield, it is necessary to define the percent of storage that is going to be accessible to those new rights, so that whenever storage contents drops below the established limit, releases for interruptible yields are curtailed.

Two case studies were analyzed, the first one considering the reservoir system analyzed in section 4.5.2 and the second one, considering Lake Waco as an individual reservoir.

4.7.1 BRA system without Allens Creek

The BRA system is the one showed in Figure 4.1 (removing Allens Creek reservoir) and evaluated in section 4.5.2. The firm yield obtained was 1,081,640 ac-ft/yr for a diversion at the Gulf of Mexico.

Four scenarios were modeled:

- Firm yield is reduced by 10%, with interruptible yields reliabilities for 75% of the demand.
- Firm yield is reduced by 10% with interruptible yields reliabilities for 100% of the demand.
- Firm yield is reduced by 20%, with interruptible yields reliabilities for 75% of the demand.
- Firm yield is reduced by 20%, with interruptible yields reliabilities for 100% of the demand.

As mentioned previously, TCEQ requires an irrigation right to meet 75% of the demand 75% of the time. Other type of rights might need a different reliability for 100% of the demand. E.g. meet 100% of the demand, 85% of the time.

For each scenario, six different amounts of conservation pool that is accessible to the interruptible yields were considered (0,20,40,60,80,100%). These levels were modeled as inactive storage for reservoirs making releases to the interruptible yield right.

Results obtained are shown in Tables 4.19 to 4.22 for each one of the four scenarios.

TABLE 4.19 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 75% of the Demand and 10% Reduction in Firm Yield

Yield reduction of 10% (108,000 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 75% demand					
50	57.33	97.27	99.71	99.71		
25,000	57.04	96.12	99.14	99.28		
50,000	56.75	94.97	97.70	99.14		
75,000	56.03	94.40	96.84	98.13		
100,000	55.46	94.25	96.41	97.27	100.00	
108,000	55.43	94.11	96.30	97.16	99.94	100.00
125,000	55.32	93.53	95.98	96.70	99.71	
150,000	55.17	92.67	95.69	96.55		
175,000	55.17	91.95	95.11	96.12		
200,000	55.17	91.38	94.54			
225,000	55.03	91.09	93.82			
250,000	55.03	90.52	93.68			
275,000	54.74	90.23	93.39			
300,000	54.02	89.51	92.96			
325,000	53.88	88.79	92.53			
350,000	53.59	88.22	91.95			
375,000	53.3	87.64	91.67			
400,000	53.16	86.93	90.66			
425,000	52.73	86.06	90.52			
450,000	52.59	85.63	89.94			
475,000	52.44	85.20	89.66			
500,000	52.01	84.20	88.94			
525,000	51.58	83.76	88.36			
550,000	51.44	82.76	87.79			
575,000	51.44	82.47	87.64			
600,000	51.44	81.75	86.93			
625,000	51.15	81.18				
650,000	51.15	80.75				
675,000	51.01	79.89				
700,000	51.01	79.31				
725,000	50.72	78.74				
750,000	50.72	78.59				
775,000	50.43	77.59				
800,000	50.43	76.72				
825,000	49.86	76.29				
850,000	49.57	76.15				
875,000	49.43	76.01				
900,000	48.99	75.43				
70,000,000	0.14	0.14				

Table 4.19 shows results for a firm yield decrease of 10% and reliabilities for 75% of the demand. If there is no storage available to the interruptible diversion, demands are only met from unappropriated flows and can give a maximum reliability of 57%, this reliability is not enough for an irrigation right. The maximum target for the interruptible yield right before having zero reliability is 70,000,000 ac-ft/yr with a reliability of 0.14%.

If 20% of the storage capacity in each reservoir is accessible to the interruptible right, then the maximum target for an irrigation right could be around 900,000 ac-ft/yr. This value corresponds to 75% reliability for 75% of the target, and the same 70,000,000 ac-ft/yr is the maximum target possible for a non zero reliability for the interruptible right, and a 100% reliability for the 90% firm yield right.

If 40% of the storage capacity in each reservoir is accessible to the new right, then the maximum possible target for the irrigation right would be 600,000 ac-ft/yr with a reliability of 86.93%. A higher target is not possible, since it would affect the 90% firm yield right and it would no longer have 100% reliability.

If 60% of the storage is available to the interruptible right, a maximum yield of 175,000 ac-ft/yr is possible, with a reliability of 96.12%. In the case of 80% of storage available to the right, the maximum yield is 125,000 ac-ft/yr with a 99.71% reliability.

Having access to all the storage capacity, a yield of 108,000 ac-ft/yr with a 100% reliability is achieved. This value is the same as the decreased portion in the firm yield.

As the interruptible right has access to more storage, reliabilities for a specific yield increase, but the maximum possible yield decrease, since a greater portion of the storage has to be divided into two rights (firm yield and interruptible yield rights).

There is an optimum value of storage accessible to the interruptible right, that maximizes the interruptible yield, and it must be calculated by trial and error. In this case it can be somewhere near 20%.

If the criteria for the new interruptible right is changed to a reliability of 90% for 75% of the demand, then with access to 20% of the storage, the target would be near 275,000 ac-ft/yr. If the access to storage is increased to 40%, then the target increases to 450,000 ac-ft/yr. For percents of 0,60,80 and 100 of storage accessible to the new right, no target would satisfy the 90% reliability criteria. In this case the optimal value of storage accessible to the new right would be somewhere 40%.

For a scenario where the firm yield is reduced by 10% and reliabilities are for 100% of the demand, the maximum possible targets for each level of storage accessible to the right are the same as those with reliabilities for 75% of the demand, but their reliabilities are smaller. Table 4.20 shows results for this scenario. For a scenario in which the firm yield is reduced by 20% and reliabilities are for 75% of the demand, results are shown in Table 4.21.

If no storage is available for the new interruptible right, the maximum reliability is around 59%, while if 20% of the storage in each reservoir is available to the new right, a yield of around 980,000 ac-ft/yr would have a 75% reliability. Values greater than 70,000,000 ac-ft/yr would give a zero reliability but would not affect the remaining 80% firm yield reliability of 100%.

If 40% of the storage is available to the new water right, then a 75% reliability yield would be around 1,425,000 ac-ft/yr, which id 525,000 ac-ft/yr greater than the 75% reliability yield achieved with a 10% reduction on the firm yield. A diversion target of 70,000,000 ac-ft/yr does not affect the remaining 80% firm yield reliability.

With access to 60% of the storage, a maximum yield of 1,000,000 ac-ft/yr with a 86% reliability can be reached, while with access to 80% of the storage, the maximum yield would be 300,000 ac-ft/yr with a 97% reliability. Finally, if the interruptible yield right has access to 100% of the storage, then the maximum yield would be 223,000 ac-ft/yr.

If reliabilities are for 100% of the demand, and the firm yield is reduced by 20%, results are shown in Table 4.22.

If firm yield is decreased, interruptible yields may be highly increased, but there is a limit on the amount the firm yield can be reduced and that limit is defined by all the contracts that the BRA has to serve, and that require 100% reliability.

In order to maximize both, firm yields and interruptible yields, different combinations of reduction in firm yield and percent of storage available to the interruptible yield must be evaluated.

TABLE 4.20 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 100% of the Demand and 10% Reduction in Firm Yield

Yield reduction of 10% (108,000 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 100% demand					
50	46.12	97.27	99.71	99.71	99.71	
25,000	46.41	95.98	99.14	99.28	99.28	
50,000	46.98	94.83	97.70	99.14	99.14	
75,000	47.41	94.40	96.41	98.13	98.99	
100,000	47.56	94.11	96.12	96.98	98.56	
108,000	47.62	93.88	96.06	96.92	98.50	100.00
125,000	47.84	92.96	95.83	96.70	98.28	
150,000	48.42	92.67	95.26	96.41		
175,000	48.56	91.24	94.68	95.98		
200,000	48.71	91.09	94.40			
225,000	48.99	90.52	93.53			
250,000	49.43	90.09	93.25			
275,000	49.57	89.51	93.10			
300,000	50.43	88.94	92.53			
325,000	50.57	88.36	91.95			
350,000	50.72	87.21	91.24			
375,000	51.01	87.21	91.09			
400,000	51.15	86.06	90.37			
425,000	51.15	85.20	89.94			
450,000	51.44	84.77	89.22			
475,000	51.44	83.76	88.79			
500,000	51.58	83.48	88.07			
525,000	52.01	83.05	87.79			
550,000	52.44	81.75	87.36			
575,000	52.73	81.18	87.21			
600,000	53.16	80.60	86.49			
625,000	53.45	79.74				
650,000	53.88	79.45				
675,000	54.02	78.16				
700,000	54.89	78.02				
725,000	55.03	77.16				
750,000	55.17	76.87				
775,000	55.17	76.58				
800,000	55.32	76.01				
825,000	55.46	75.14				
850,000	56.18	74.86				
875,000	57.04	74.43				
900,000	57.33	73.56				
70,000,000	0.14	0.14				

TABLE 4.21 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 75% of the Demand and 20% Reduction in Firm Yield

Yield reduction of 20% (217,000 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 75% demand					
50	58.91	97.99				
40,000	58.33	96.41	100.00			
50,000	58.33	95.98	98.99	100.00		
100,000	58.05	95.26	97.70	99.28	100.00	
150,000	57.61	94.25	96.41	97.99	99.28	
200,000	56.90	92.82	95.69	97.27	98.99	
220,000	56.44	92.30	95.52	96.93	98.59	100.00
223,000	56.37	92.25	95.50	96.90	98.55	99.90
250,000	55.75	91.52	95.26	96.41	97.99	
300,000	55.46	90.37	94.11	96.12	97.13	
350,000	55.17	89.51	93.53	95.26		
400,000	55.03	88.51	92.67	94.83		
450,000	54.31	87.36	91.95	94.40		
500,000	53.88	86.21	90.80	93.53		
550,000	53.45	84.48	89.80	92.96		
600,000	53.02	83.19	88.79	92.10		
650,000	52.59	82.18	87.79	91.67		
700,000	52.01	81.32	86.93	90.95		
750,000	51.58	80.32	86.49	89.66		
800,000	51.58	78.16	85.06	89.37		
850,000	51.44	77.44	84.05	88.36		
900,000	50.86	76.87	83.62	87.50		
950,000	50.57	75.72	83.33	86.64		
1,000,000	49.86	74.71	81.75	86.21		
1,050,000	49.28	73.85	81.32			
1,100,000	48.99	72.84	80.46			
1,150,000	48.56	72.27	80.17			
1,200,000	48.13	70.98	79.45			
1,250,000	47.56	69.83	78.16			
1,300,000	46.98	68.97	77.59			
1,350,000	46.70	68.53	76.58			
1,400,000	46.70	67.96	75.57			
1,450,000	46.12	66.67	74.86			
1,500,000	45.83	66.38	73.99			
70,000,000	0.14	0.14	0.14			
> 70,000,000	0.00	0.00	0.00			

TABLE 4.22 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 100% of the Demand and 20% Reduction in Firm Yield

Yield reduction of 20% (217,000 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 100% demand					
50	58.91	97.99				
40,000	58.33	96.41	100.00			
50,000	58.33	95.98	98.99			
75,000	57.97	95.55	98.28	100.00		
100,000	57.61	95.11	97.56	99.14	100.00	
150,000	56.90	93.97	96.41	97.84	99.28	
200,000	55.60	92.53	95.69	97.13	98.85	
217,000	55.45	92.14	95.45	96.88	98.41	100.00
223,000	55.40	92.00	95.36	96.79	98.26	99.43
250,000	55.17	91.38	94.97	96.41	97.56	
300,000	55.03	89.94	93.82	95.83	96.98	
350,000	54.17	88.36	92.82	94.83		
400,000	53.45	88.07	92.10	94.54		
450,000	53.02	86.21	91.52	93.97		
500,000	52.16	85.34	90.09	92.82		
550,000	51.72	83.48	89.37	91.95		
600,000	51.58	82.18	87.93	91.24		
650,000	51.15	81.32	87.07	91.09		
700,000	50.72	79.60	86.35	90.66		
750,000	49.86	78.02	85.63	89.37		
800,000	49.28	77.16	84.48	88.94		
850,000	48.71	75.86	83.48	87.79		
900,000	48.13	75.43	82.76	86.93		
950,000	47.27	72.99	81.61	86.06		
1,000,000	46.70	72.27	81.18	85.20		
1,050,000	46.70	71.41	80.17			
1,100,000	45.98	70.40	79.31			
1,150,000	45.55	69.68	78.02			
1,200,000	44.83	68.53	76.87			
1,250,000	44.25	67.82	76.29			
1,300,000	43.53	66.67	75.43			
1,350,000	43.39	65.80	74.28			
1,400,000	42.96	65.37	73.85			
1,450,000	42.53	64.08	72.56			
1,500,000	42.24	63.22	71.70			
70,000,000	0.14	0.14	0.14			
> 70,000,000	0.00	0.00	0.00			

4.7.2 Interruptible yields at Lake Waco

Lake Waco was not considered part of the system, since all of its water rights are held by the city of Waco.

The firm yield calculated in section 4.1 was 93,120 ac-ft/yr when not considering Allens Creek reservoir. This firm yield was calculated using the weighted water use coefficients; in this section, the firm yield was recalculated using the original municipal coefficients for this diversion location. The new firm yield is 92,700 ac-ft/yr. This exercise shows that depending on the water use coefficients adopted, a different value of firm yield may be calculated.

A new simplified dataset containing only Lake Waco was developed and the same four scenarios (Reductions of 10 and 20% in firm yield, for reliabilities of 75 and 100% of the demand.) evaluated for the BRA system interruptible yields were analyzed for Lake Waco. Results are shown in Tables 4.23 to 4.26

If the objective is to issue a new irrigation right, a maximum yield of 40,000 ac-ft/yr would be available for a reduction of 10% in the firm yield, while about 94,000 ac-ft/yr would be available with a reduction of 20% in the firm yield. Assume the requirements for a new municipal supply water right are 85% reliability for 100% of the demand, with the remaining 15% of the time taking water from an alternate source of water, such as an aquifer. If this is the case, from Tables 4.24 and 4.26, the results shown in Table 4.27 can be obtained. The new water right demand of 51,400 ac-ft/yr with a reliability of 85% can be met if firm yield is reduced by 20% and the water right has access to 60% of the storage capacity at Lake Waco.

Again, the calculation of the optimal value would require several iterations with different amounts of storage accessible to the new water right and a complete knowledge of the maximum percent of reduction in the firm yield that can be done.

TABLE 4.23 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 75% of the Demand and 10% Reduction in Firm Yield, Lake Waco

Yield reduction of 10% (9,270 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 75% demand					
50	30.03	71.12	87.93	95.98	99.43	
9,270	29.6	67.84	85.66	93.74	97.99	100
9,500	29.6	67.75	85.56	93.68	97.99	99.86
10,000	29.6	67.53	85.34	93.68	97.84	
14,000	29.43	65.75	83.96	91.52	96.98	
20,000	29.17	63.07	81.9	89.22		
30,000	29.17	59.63	78.02	86.64		
40,000	28.74	56.32	75.43			
50,000	28.3	54.31	72.99			
60,000	27.87	52.44	70.4			
70,000	27.59	50.72	68.1			
80,000	27.3	47.84	65.52			
90,000	27.01	46.55	62.79			
100,000	26.29	45.98	60.34			
110,000	26.29	44.83	58.19			
120,000	26.01	43.82	57.04			
130,000	25.86	42.53	55.46			
140,000	25.57	41.09	53.45			
150,000	25.43	40.09	52.16			
160,000	25.29	38.94	50.43			
170,000	24.86	37.93	48.71			
174,000	24.8	37.64	48.3			
180,000	24.71	37.21				
190,000	24.71	36.35				
200,000	24.57	35.78				
210,000	24.43	35.34				
220,000	24.43	34.77				
230,000	24.14	34.34				
240,000	24.14	33.62				
250,000	23.85	32.9				
260,000	23.56	32.76				
270,000	23.13	32.04				
280,000	22.84	31.47				
290,000	22.41	31.03				
300,000	22.41	30.6				
5,000,000	0.14	0.14				
>5,000,000	0.00	0.00				

TABLE 4.24 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 100% of the Demand and 10% Reduction in Firm Yield, Lake Waco

Yield reduction of 10% (9,270 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 100% demand					
50	30.03	71.12	87.93	95.98	99.43	
9,270	29.56	67.64	85.67	93.75	97.99	100.00
9,500	29.53	67.46	85.56	93.68	97.99	99.86
10,000	29.45	67.10	85.34	93.68	97.84	
14,000	29.34	65.32	83.96	91.52	96.98	
20,000	29.17	62.64	81.90	89.08		
30,000	28.74	59.34	77.87	86.64		
40,000	28.16	55.60	75.14			
50,000	27.87	53.59	72.56			
60,000	27.30	50.86	69.83			
70,000	26.72	48.71	67.67			
80,000	26.29	46.70	64.08			
90,000	26.01	45.83	61.49			
100,000	25.72	44.54	59.20			
110,000	25.57	43.10	57.47			
120,000	25.29	41.81	55.89			
130,000	24.86	40.66	54.17			
140,000	24.71	38.79	51.72			
150,000	24.57	37.79	50.72			
160,000	24.43	37.21	48.13			
170,000	24.28	36.64	47.27			
174,000	24.22	36.30	46.70			
180,000	24.14	35.78				
190,000	23.71	35.20				
200,000	23.13	34.34				
210,000	22.84	33.62				
220,000	22.41	32.76				
230,000	22.27	32.18				
240,000	22.27	31.90				
250,000	22.13	30.89				
260,000	21.55	29.89				
270,000	21.41	29.74				
280,000	20.83	29.60				
290,000	20.26	29.31				
300,000	20.11	28.16				
5,000,000	0.14	0.14				
>5,000,000	0.00	0.00				

TABLE 4.25 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 75% of the Demand and 20% Reduction in Firm Yield, Lake Waco

Yield reduction of 20% (18,540 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 75% demand					
50	33.05	76.44	91.81	97.99		
5,800	32.76	74.05	89.60	96.84	100.00	
10,000	31.75	71.41	88.22	95.83	99.28	
18,550	31.13	68.58	85.76	94.11	98.05	100.00
19,000	31.10	68.43	85.63	94.02	97.99	99.86
20,000	31.03	68.10	85.34	93.82	97.70	
30,000	30.60	63.51	82.33	89.80	95.26	
40,000	30.32	60.20	78.88	87.07		
50,000	30.03	57.04	76.01	85.63		
60,000	29.74	55.60	73.42	82.90		
70,000	29.60	53.45	71.41	80.75		
80,000	28.88	52.30	68.68	78.16		
90,000	28.74	48.99	65.95	76.29		
100,000	28.74	47.56	63.51	73.99		
110,000	28.02	46.70	60.92	71.84		
120,000	27.01	45.69	59.05	69.68		
128,000	26.90	44.88	57.67	68.40		
130,000	26.87	44.68	57.33			
140,000	26.58	43.39	55.89			
150,000	26.15	42.39	54.17			
160,000	26.01	40.95	53.02			
170,000	25.86	39.80	51.44			
180,000	25.72	38.51	49.43			
190,000	25.57	38.07	48.28			
200,000	25.57	37.21	47.13			
210,000	25.29	36.49	46.12			
220,000	25.29	35.92	44.68			
230,000	25.14	35.63	43.53			
240,000	24.86	35.06	42.82			
250,000	24.71	34.91	42.10			
260,000	24.57	33.91	40.95			
270,000	24.43	33.48	40.09			
280,000	23.71	32.90	39.37			
290,000	23.42	32.33	38.36			
300,000	23.13	31.75	38.07			
2178000	4.20	4.60	4.70			
5,000,000	0.14	0.14				
>5,000,000	0.00	0.00				

TABLE 4.26 Interruptible Yield Versus Reliability for Access to Different Percents of Storage, Reliabilities for 100% of the Demand and 20% Reduction in Firm Yield, Lake Waco

Yield reduction of 20% (18,540 ac-ft/yr)						
Yield (ac-ft/yr)	% of conservation pool accessible to Interruptible yields					
	0%	20%	40%	60%	80%	100%
	Interruptible Yield Reliability (%) for 100% demand					
50	33.05	76.44	91.81	97.99		
5,800	32.18	73.51	89.59	96.84	100.00	
10,000	31.75	71.26	88.22	95.83	99.14	
18,550	30.77	67.82	85.76	93.86	97.91	100.00
19,000	30.72	67.64	85.63	93.76	97.84	99.86
20,000	30.60	67.24	85.34	93.53	97.70	
30,000	30.32	63.36	82.33	89.66	95.11	
40,000	30.03	59.34	78.30	86.93		
50,000	29.60	56.03	75.72	85.34		
60,000	28.88	54.02	73.13	82.90		
70,000	28.74	52.16	70.69	80.03		
80,000	28.30	49.71	67.96	77.44		
90,000	27.01	47.56	64.51	75.14		
100,000	26.87	46.55	61.78	72.70		
110,000	26.15	44.97	59.48	71.26		
120,000	26.01	43.82	57.61	68.82		
128,000	25.89	42.56	56.23	62.64		
130,000	25.86	42.24	55.89			
140,000	25.72	41.24	54.31			
150,000	25.57	39.66	52.73			
160,000	25.29	38.36	50.57			
170,000	25.14	37.93	48.71			
180,000	24.86	37.36	47.70			
190,000	24.57	36.35	46.41			
200,000	24.43	35.78	44.83			
210,000	23.71	34.77	43.53			
220,000	23.28	34.05	42.96			
230,000	22.99	33.48	41.81			
240,000	22.84	33.19	40.80			
250,000	22.84	32.90	39.80			
260,000	22.70	31.90	38.79			
270,000	21.98	30.75	38.07			
280,000	21.98	27.73	34.48			
290,000	21.70	27.73	33.91			
300,000	21.26	27.16	32.76			
2178000	2.73	3.02	3.30			
5,000,000	0.14	0.14				
>5,000,000	0.00	0.00				

TABLE 4.27 Maximum Interruptible Yields (ac-ft/yr) for a Right With Reliability of 85% for 100% of the Demand, at Lake Waco

	% of conservation pool accessible to Interruptible yields					
Yield reduction	0%	20%	40%	60%	80%	100%
10%	-	-	10,985	30,000	14,000	9,500
20%	-	-	21,130	**51,400**	30,000	19,000

4.8 IMPACT OF BEGINNING STORAGE ON RELIABILITIES AND YIELDS

WRAP as any other computer model requires an initial condition in order to perform any analysis. By default, in WRAP, reservoirs are assumed to be full at the beginning of the simulation, if not otherwise specified on WS records. All the datasets developed for the WAM project assume reservoirs are full at the beginning of the simulation; this assumption may lead to untrue results, such as reliabilities, storage frequencies or reservoir yields.

Recently WRAP was added a new capability of performing cycling, which performs the simulation a second time, storages at the end of the first simulation become the storages at the beginning of the second simulation. The objective of this chapter is to evaluate the impact of assuming reservoirs starting at full capacity or using the cycling option.

4.8.1 Reliabilities

An analysis was performed for the Brazos River Basin consisting on simulating the WAM dataset for full authorization amounts, starting with reservoirs full or using the cycling option. The Brazos WAM dataset has a total of 661 reservoirs, after the simulation starting with all reservoirs full, 236 reservoirs representing 43% of the total basin storage capacity remained full and 425 didn’t. The total storage at the end of the simulation was 81.6% of the total basin capacity.

When using the cycling option, storages at the end of the initial simulation become initial storages for the second simulation; so the second simulation started with a total storage of 81.6% of the total basin capacity. The ending storages for the second simulation were the same as the initial ones.

The Brazos River Basin has a total of 1618 water rights, 310 of those have no diversion target. Period reliabilities were calculated for each one of the remaining 1308 rights, with the following results being obtained:

- A total of 7 water rights increased their reliabilities after using cycling; all of these water rights are backup rights and their increase was less than 1%.
- A total of 269 water rights decreased their reliabilities, with differences that range from 0 to 10%. The distribution of values is shown in Table 4.28

TABLE 4.28 Distribution of Variation in Reliabilities for the Brazos River Basin

Difference (%)	Number of Water Rights
0.0 - 0.5	152
0.5 - 1.0	53
1.0 - 1.5	31
1.5 - 2.0	9
2.0 - 3.0	19
3.0 - 4.0	2
4.0 - 10	3

20% of the total number of water rights in the basin was affected, which to the author's opinion is a high proportion. Although the magnitude of change in most of them is small, for others is quite significant.

The Guadalupe and San Antonio River Basins were analyzed as well, this dataset includes 1,334 control points, 853 water rights and 233 reservoirs; the following results were obtained:

- 126 of the 853 water rights are no diversion rights
- 512 of the remaining rights didn't have any change in their reliabilities
- 13 rights increased their reliabilities by less than 0.5%
- A total of 202 rights decreased their reliabilities that range from 0 to 4.8% with Table 4.29 showing the distribution of these values.

TABLE 4.29 Distribution of Variation in Reliabilities for the Guadalupe and San Antonio Basins

Difference (%)	Number of Water Rights
0.0 - 0.5	134
0.5 - 1.0	41
1.0 - 1.5	20
1.5 - 2.0	0
2.0 - 3.0	3
3.0 - 4.0	3
4.0 - 5.0	1

Once more over 30% of the rights was affected, with differences being smaller in magnitude to those obtained for the Brazos River Basin. To the author's opinion, although the impact of recycling in these two cases affects more than 20% of the rights, it could be worse if the first simulated years were dry years. In this case initial years were wet years, which contributed to decrease the impact of cycling on great part of the rights. In the case of having dry years at the beginning of the simulation, most likely a higher proportion of water rights may become affected or the magnitude of change increase.

In order to test the impact of dry years at the beginning of the simulation, the two previously analyzed basins were modified, to start the simulation at 1950, which was the starting year of the most severe drought of record in Texas. The following results were obtained for the Brazos River Basin:

- The total storage at the end of the first simulation was 81.7%, 0.1% higher than the simulation that started in 1940
- A total of 984 rights remained unchanged, 48 less than the other simulation
- A total of 15 rights increased their reliabilities, 13 between 0 and 1% and 2 between 1 and 1.22%
- A total of 307 rights were negatively affected: Table 4.30 shows the distribution of these changes

TABLE 4.30 Distribution of Variation in Reliabilities for the Brazos River Basin With Simulation Starting in 1950

Difference (%)	Number of Water Rights
0.0 - 0.5	109
0.5 - 1.0	74
1.0 - 1.5	42
1.5 - 2.0	20
2.0 - 3.0	35
3.0 - 4.0	20
4.0 - 10.93	7

For the Guadalupe and San Antonio Basins, obtained results were as follows:

- The total storage at the end of the first simulation was 53.6% which is the same amount as for the simulation starting in 1934
- A total of 559 rights remained unchanged, 47 more than with the other simulation
- 3 rights increased their reliabilities, 2 between 0 and 0.5% and 1 between 0.5 and 0.62%
- A total of 165 rights were negatively affected: Table 4.31 summarizes the distribution of these changes.

TABLE 4.31 Distribution of Variation in Reliabilities for the Guadalupe and San Antonio Basins With Simulation Starting in 1950

Difference (%)	Number of Water Rights
0.0 - 0.5	82
0.5 - 1.0	21
1.0 - 1.5	32
1.5 - 2.0	12
2.0 - 3.0	3
3.0 - 4.0	12
4.0 - 5.0	3

From the previous results, it is possible to conclude that applying cycling to a simulation starting with wet years has less impact on water rights than when starting the simulation with dry years. Although in some cases the total number or affected rights decreased, the magnitude of the differences actually increased.

4.8.2 Impact in firm yield analysis

The same dataset used for section 4.6 to model the BRA system, was used for this analysis in order to measure the impact of the initial storage in the final firm yield at the Gulf of Mexico. This dataset uses the dual simulation option that was described in previous sections. The procedure followed to perform the analysis was the following:

- The dataset was run to determine the firm yield at the Gulf of Mexico, obtaining a value of 1,188,100 ac-ft/yr
- This value was added as a fixed target for the water right at the Gulf of Mexico; a first simulation was run, in order to determine the end of period storages, which were written to a BES file, using BES option 1. These storages represent the values at the end of the simulation
- A second simulation was run, reading the initial storages from the BES file for both, the initial and the second pass of the dual option
- Reliabilities were checked for the system right and were confirmed to be 100%

In this case, the firm yield was not affected when using recycling, this may be explained because almost all the reservoirs included in the system are full or almost full, and the first years of the simulation are wet years, so they easily refill their conservation pools.

As in the previous section, the simulation period was modified to analyze the results if the first years of the simulation were dry years. The period of analysis was changed to 1950 to 1997. These are the results:

- The firm yield at the Gulf of Mexico increased to 1,191,700 ac-ft/yr, due to the fact that this initial simulation does not use cycling, so reservoirs start full at 1950 which was a dry year. In the previous exercise, in 1950 reservoirs were not full, so reliabilities are being increased in this initial simulation.
- A second simulation was run, with end of period storages from the previous simulation becoming initial storages for 1950 and a fixed target of 1,191,700 ac-ft/yr for the system right at the Gulf of Mexico

- The final reliability for this right was not 100%, so the original firm yield was affected because of starting the simulation with dry years.
- After changing the diversion target value for the system right, a final firm yield of 1,190,050 ac-ft/yr was found, 1,650 ac-ft/yr less than the one obtained with wet years at the beginning of the simulation.

CHAPTER V

CONDITIONAL RELIABILITY MODELING

Conditional Reliability Modeling is a technique used to estimate short term reliability and frequency, conditioned on preceding reservoir storage. In order to do so, the hydrologic period of analysis of a long term simulation is divided into multiple short term sequences and each sequence is simulated starting always with the same initial storage.

A long term reliability analysis such as the one performed by WRAP, assumes all reservoirs start the simulation full or may adopt a cycling option in which end of simulation storages become initial storages for a new simulation. This long term reliability does not reflect the fact that reservoir managers know current storage levels, something crucial when determining reliabilities a few months into the future. If a reservoir is 80% full, the likelihood of being full in 6 months into the future is greater than if it is 20% full now.

A typical long term simulation with a period of analysis from 1940-1997 can be divided into 58 annual sequences, or 696 monthly sequences. The system is simulated 58 or 696 times with equal number of different naturalized streamflow and net evaporation sequences, with each simulation sequence having a fixed initial reservoir storage level. Reliability estimates are developed from the simulation results.

Different methodologies have been developed to perform a conditional reliability analysis: (1) counting the number of times a specific value of reservoir storage or diversion target is equaled or exceeded within the total number of simulations, this analysis assumes each simulation has the same probability to occur (i.e., Equally likely). (2) Salazar (*11*) developed a technique in which the likelihood of each simulation is not the same, it depends on the initial storage condition. This technique is called Conditional Frequency Duration Curves. And (3) a new methodology developed in this thesis called Storage-Flow Frequency (SFF) that assigns different probabilities of occurrence to each sequence based on the relationship between preceding reservoir storage volume and the naturalized streamflow volume during the following specified number of months.

Results obtained from each technique are compared and discussed, trying to identify patterns, complexities, advantages or disadvantages and guidelines for each technique.

5.1 CONDITIONAL FREQUENCY DURATION CURVE (CFDC) TECHNIQUE

5.1.1 Description of the model

As previously mentioned, the CFDC technique was developed by Salazar (*11*). This methodology assigns different probabilities of occurrence for each sequence, depending on the initial storage content in the reservoir or reservoirs being analyzed. The CFDC is based on a WRAP long term simulation, storage capacity is divided into several intervals representing different levels, i.e. High, medium, and low storage. The naturalized flow series is divided into equal number of intervals, having one array of flows for each storage level. Each array of flows contains the flows that followed the occurrence of each storage level. For example, the array of flows corresponding to high storage, will include all those flows that followed a month with a high storage. A statistical analysis using the Weibull formula assigns probabilities to each naturalized flow given the occurrence of a storage level.

A CFDC is developed considering storage levels at each month of the long term simulation and the naturalized flows that followed. Conditional Frequency Duration Curves varies with time; a CFDC for 1 month will take into account flows that occurred one month after the storage value being considered, while a CFDC for 3 months will consider flows that occurred in the next 3 months. A 58 year simulation will have 696 months, end of period storage in each month is read and classified within the previously specified intervals; cumulated naturalized flows over the next N months are stored in the naturalized flows array corresponding to each storage level.

After developing the CFDC and running the different initial storage conditions, it is possible to compute conditional reliability of storage and diversions. In the case of storages, reliabilities are calculated for the last month of the period of analysis. In the case of diversions, reliabilities are calculated for the entire period of analysis as the sum of diversions made divided by the sum of diversion targets. Naturalized flows are also cumulated over the period of analysis and an array containing either storage or cumulated diversions and the cumulated flows over the period of analysis is built. It is assumed that a higher flow will produce an equal or greater diversion amount, therefore, the probability of equaling or exceeding the computed storage or average diversion amount is equal to the probability of equaling or exceeding the corresponding cumulated naturalized flow. This probability is obtained from the CFDC.

The CFDC modeling technique is highly dependant on the autocorrelation of flows. If flows are autocorrelated, a future flow may be derived partially from previous flows. If flows are not autocorrelated, it may not be possible to develop a meaningful CFDC, and the assumption of any flow sequence having the same probability of occurrence may be as accurate as the CFDC technique.

When considering reliabilities more than one month into the future, as mentioned previously, an average diversion is computed over the period of analysis. It is possible to obtain results where a greater naturalized flow may produce a lower diversion than the one obtained from a smaller naturalized flow. Assume a period of analysis of 3 months, in the first case flows are evenly distributed over time and diversions targets are met at all 3 months; in the second case the first two months were dry months, with diversions on these two months not meeting the target, but the third month was a flood month and diversion targets were met. In the first case, average diversions will be 100%, while in the second case it will be less than 100% with cumulative flows could being greater in the second case than in the first one.

Because of this situation, it is necessary to develop a naturalized flow-diversion or storage relationship, where for each value of naturalized flow there is a unique value of diversion or storage. This relationship is developed by using two different regression techniques, linear and S-curve regressions. In the case of diversions, the regression analysis is done using cumulated naturalized flows and average diversion, both over the period of analysis. When analyzing storage, naturalized flows are cumulated over the period of analysis and reservoir storage corresponds to the end of period storage of the last month in the analysis. The model applies both regression techniques and chooses the one with the highest correlation coefficient. The selected regression is applied to the naturalized flows and a unique relationship between naturalized flows and diversion/storage is found.

In order to assign probabilities to each diversion or storage value, the CFDC is applied to the naturalized flow-diversion/storage relationship, and a reliability curve for diversion or storage is obtained. Table 5.1 shows a 6 months CFDC that will be applied to Figure 5.1 in order to get the reliability curve shown in Figure 5.2. The initial storage of the simulation corresponds to a low storage level.

TABLE 5.1 6 Months CFDC for Naturalized Flow at a Control Point

Storage Level	Mean	% of months equaling or exceeding total naturalized flow in table							
		100%	95%	90%	75%	50%	25%	10%	MAX
Low	40371	3167	10069	14159	25699	70969	166886	279295	710441
Medium	57396	2693	14589	20292	40987	85405	221682	403716	825336
High	169767	10734	37563	48526	88349	190888	324140	645082	1296383

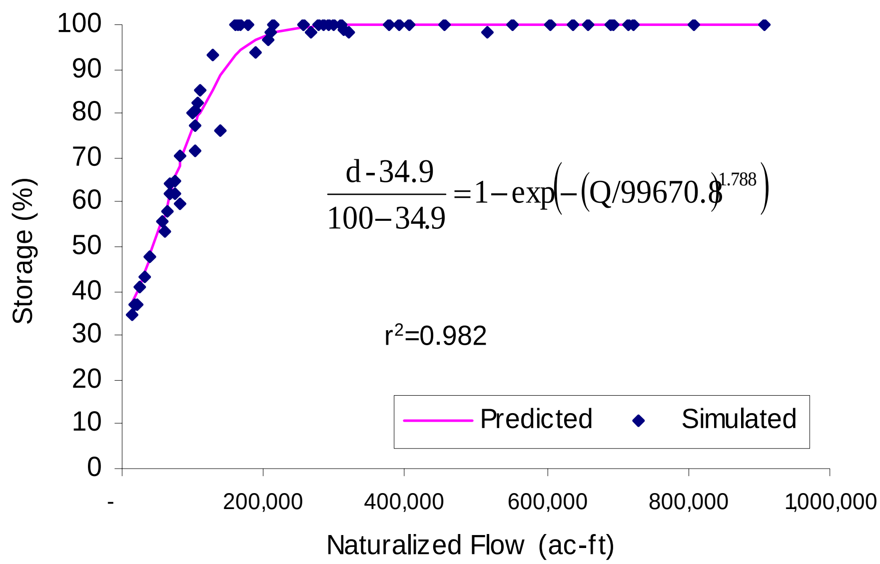


FIGURE 5.1 Example of relationship of flow vs storage as a percent of capacity.

A naturalized flow of 100,000 ac-ft over the next 6 months will produce a storage of 73% of the capacity. A flow of 100,000 ac-ft under low storage conditions has an exceedance probability of about 41%, therefore a storage of 73% will be exceeded 41% of the time 6 months from now.

The expected value of diversion or volume reliability is calculated as the area under the reliability curve. In the case of Figure 5.2 the volume reliability is 67% and the period reliability is 9.86% which is the probability that corresponds to 100% of storage.

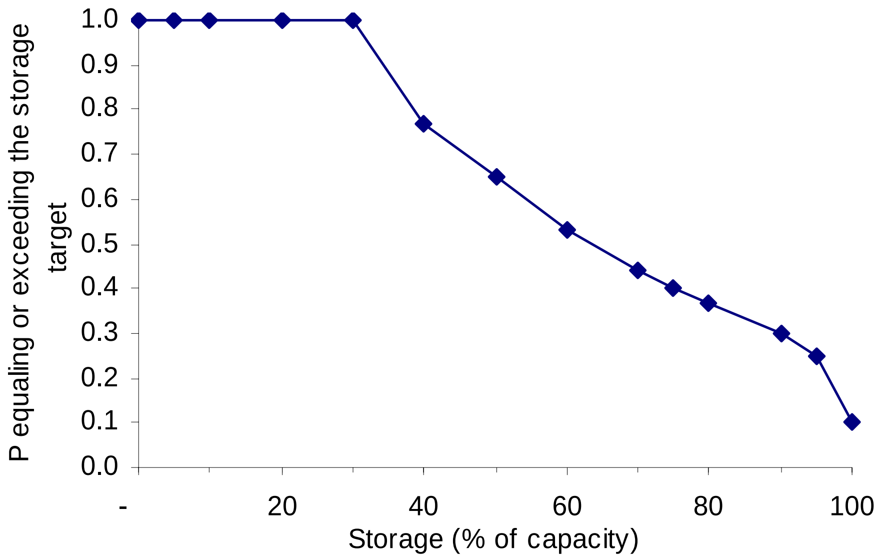


FIGURE 5.2 Reliability curve for storage over the next 6 months

5.1.2 Improvements made to the model

The current version of WRAPCON and TABCON includes some improvements from the previous version created by Salazar (*11*).

- WRAPCON and TABCON are now dynamic dimensioning programs; this translates into removing the imposition of dimension limits on model applications. The number of variables can exceed the previously allowed limits and memory requirements are reduced because the arrays are only as large as needed.
- The WRAPCON code was merged to the May 2004 version of WRAP-SIM, including new modeling features that are fully described by Wurbs (*4*).
- Subroutines responsible to develop the storage/diversion naturalized flow relationship were modified to improve the regression results.
- The subroutine that calculates correlation coefficients between storage and flows was highly modified, to include new features that facilitate the evaluation of correlation between flows at a control point and a combination of reservoirs.
- A new type of records (type 4) was created, to allow the user to develop conditional frequency duration curves and correlation analysis without having to

run WRAPCON, since these analysis are solely based on a conventional WRAP simulation.

5.1.3 Methodologies to apply the model

The basic procedures followed by the model were discussed in the previous section, but there are many aspects of the model that have to be considered carefully because of their great impact when calculating reliabilities. These aspects are the effect of the initial storage in a long term simulation and the selection of reservoirs to build a CFDC.

Effect of initial storage in a long term simulation

As explained in section 4.8 the definition of the initial storage for a long term simulation, may have an impact on its results. Since Conditional Frequency Duration Curves are based on a long term simulation, this issue has to be addressed by using the cycling option. This option performs a second simulation, where the end of period storages for the first simulation become the initial storages for the second one.

Analysis of correlation between storage and flow

As explained previously, the conditional reliability model is based on the assumption of naturalized flows at a specific control point, being correlated with reservoir storage. This correlation may also exist between a control point and several other reservoirs. Operational rules in a river basin may affect greatly this correlation and therefore affect the CFDC and the conditional reliability results.

If a basin has a system of reservoirs, and releases depend on the storage in each reservoir, storage will vary according to the operational rules and modification of these rules may result in a modification of the CFDC. It may be possible that the flows at the diversion location of the system are correlated to all reservoirs in the system instead of one single reservoir. In order to build a more representative CFDC, different combinations of reservoirs have to be analyzed. In order to perform this analysis, the model has two different statistical parameters: Linear and Spearman’s coefficients.

The linear correlation coefficient measures the strength of a linear relationship between two variables. It has a value between 1 and -1. The Spearman's coefficient provides a measure of how closely two sets of rankings agree with each other. The two variables that are being analyzed are the reservoir storage in one or more reservoirs and the cumulated naturalized flow over a period of time at the control point of interest.

Two control points and 12 reservoirs from the Brazos River Basin were analyzed to find those reservoirs that correlate the best to control points 515531 and 515631 (Possum Kingdom and Granbury). Tables 5.2 to 5.5 show linear and Spearman correlation coefficients for each control point, for 1 month, 3 months and 6 months into the future. For each period of analysis, the 4 highest values were selected and are highlighted in red. Next, the 3 reservoirs with the highest number of highlighted values were selected. For control point 515531 the selected reservoirs are Possum Kingdom, Granbury and Waco; for control point 515631 the selected reservoirs are Granbury Whitney and Waco. Notice that Proctor reservoir has a good linear correlation, but the Spearman correlation is not that good. Control point 515631 has better linear correlation with Possum Kingdom reservoir than with Granbury reservoir which is located at that control point; this may be caused because both reservoirs are on the same stream and Possum Kingdom is located upstream and is senior to Granbury. In general these to control points are related to reservoirs in the upper middle basin (Figure 4.2), those reservoirs in the lower middle basin and lower basin have low correlation values.

The Spearman's coefficients are higher than the linear ones because this technique considers other relationships besides linear. Both linear and Spearman coefficients decrease as the period of analysis increases, at a certain point the correlation will be very low, that it may not be possible to develop a realistic CFDC.

Analysis of a reservoir combination

With the reservoirs selected from the previous section, it is possible to build different combinations to be correlated with naturalized flows at a certain control point. In this case combinations showed in Tables 5.6 and 5.7 were analyzed for control points 515531 and 515631 respectively. Notice that for 515531, Possum Kingdom was included in all combinations while for 515631, Granbury reservoir was always included;

TABLE 5.2 Linear Correlation Coefficients Between Reservoir Storage and Naturalized Flow for Control Point 515531

Period	Reservoir											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1	**0.1030**	**0.0770**	0.0740	0.0661	0.0735	**0.0888**	0.0366	0.0443	**0.0814**	0.0729	0.0460	0.0503
3	**0.0825**	**0.0483**	**0.0567**	**0.0436**	-0.0102	0.0380	-0.0321	-0.0063	0.0326	0.0114	-0.0056	0.0156
6	**0.0143**	**0.0202**	**0.0404**	0.0090	-0.0933	-0.0303	-0.0867	-0.0544	-0.0139	-0.0399	-0.0680	-0.0313

TABLE 5.3 Spearman Correlation Coefficients Between Reservoir Storage and Naturalized Flow for Control Point 515531

Period	Reservoir											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1	**0.3143**	0.2534	**0.2885**	0.2595	**0.2857**	**0.2770**	0.2314	0.2175	0.2320	0.2587	0.1802	0.2434
3	0.1682	0.1816	0.1952	**0.2158**	**0.2322**	**0.2627**	0.1665	0.1615	0.1927	**0.2219**	0.1686	0.2106
6	0.0698	0.0875	0.1352	**0.1426**	0.1257	**0.1702**	0.0964	0.1026	0.1264	**0.1655**	**0.1436**	0.1421

TABLE 5.4 Linear Correlation Coefficients Between Reservoir Storage and Naturalized Flow for Control Point 515631

Period	Reservoir											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1	**0.1223**	0.1048	0.1145	0.1063	**0.1154**	**0.1311**	0.0733	0.0728	**0.1162**	0.1078	0.0692	0.0679
3	**0.1053**	0.0672	**0.0916**	**0.0840**	0.0222	**0.0743**	0.0065	0.0220	0.0616	0.0398	0.0067	0.0182
6	**0.0400**	**0.0362**	**0.0700**	**0.0502**	-0.0750	-0.0065	-0.0455	-0.0229	0.0116	-0.0138	-0.0655	-0.0447

TABLE 5.5 Spearman Correlation Coefficients Between Reservoir Storage and Naturalized Flow for Control Point 515631

Period	Reservoir											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1	**0.3145**	0.2756	**0.3204**	0.2856	**0.2954**	**0.2983**	0.2654	0.2369	0.2566	0.2758	0.2124	0.2551
3	0.1769	0.1978	0.2188	**0.2332**	**0.2316**	**0.2775**	0.2008	0.1788	0.2118	**0.2382**	0.1927	0.2159
6	0.0826	0.0987	**0.1480**	**0.1524**	0.1105	**0.1731**	0.1206	0.1126	0.1384	**0.1730**	0.1445	0.1254

this is because those reservoirs are located at the respective control point and it is assumed that a coherent combination should include the local reservoir.

TABLE 5.6 Reservoir Combinations Analyzed for Control Point 515531

Combination	Reservoirs		
	Possum	Granbury	Waco
A	X		
B	X	X	
C	X		X
D	X	X	X

TABLE 5.7 Reservoir Combinations Analyzed for Control Point 515631

Combination	Reservoirs		
	Granbury	Whitney	Waco
A	X		
B	X	X	
C	X		X
D	X	X	X

Linear and Spearman's correlation coefficients were calculated for 1, 3 and 6 months for each combination. Results are shown in Tables 5.8 and 5.9 for control points 515531 and 515631 respectively. Highlighted values represent the combination with the highest coefficient for each period.

TABLE 5.8 Linear and Spearman's Coefficients for Reservoir Combinations at 515531

Period	Coefficient	Reservoir combination			
		A	B	C	D
1	Linear	0.1030	0.1021	**0.1132**	0.1096
3	Linear	**0.0825**	0.0811	0.0791	0.0777
6	Linear	0.0143	**0.0223**	0.0009	0.0096
1	Spearman	0.3143	0.3201	0.3347	**0.3362**
3	Spearman	0.1682	0.1792	0.2166	**0.2188**
6	Spearman	0.0698	0.0836	0.1164	**0.1195**

TABLE 5.9 Linear and Spearman's Coefficients for Reservoir Combinations at 515631

Period	Coefficient	Reservoir combination			
		A	B	C	D
1	Linear	0.1145	0.1144	**0.1381**	0.1275
3	Linear	0.0916	0.0908	0.0912	**0.0917**
6	Linear	**0.0700**	0.0592	0.0298	0.0423
1	Spearman	0.3204	0.3069	**0.3345**	0.3278
3	Spearman	0.2188	0.2373	**0.2717**	0.2697
6	Spearman	0.1480	0.1558	0.1749	**0.1770**

For control point 515531, the highest coefficients correspond to combination D which involves Possum Kingdom, Granbury and Waco reservoirs. For control point 515631, the highest coefficients correspond to combination C, which includes Granbury and Waco reservoirs; for this control point, correlation coefficient values are higher than those obtained for 515531. Notice that for 6 months, the highest correlation values are not for combination C, it is recommended to have a unique combination for each control point, unless there is a specific reason to have multiple combinations depending on the period of analysis (operating rules).

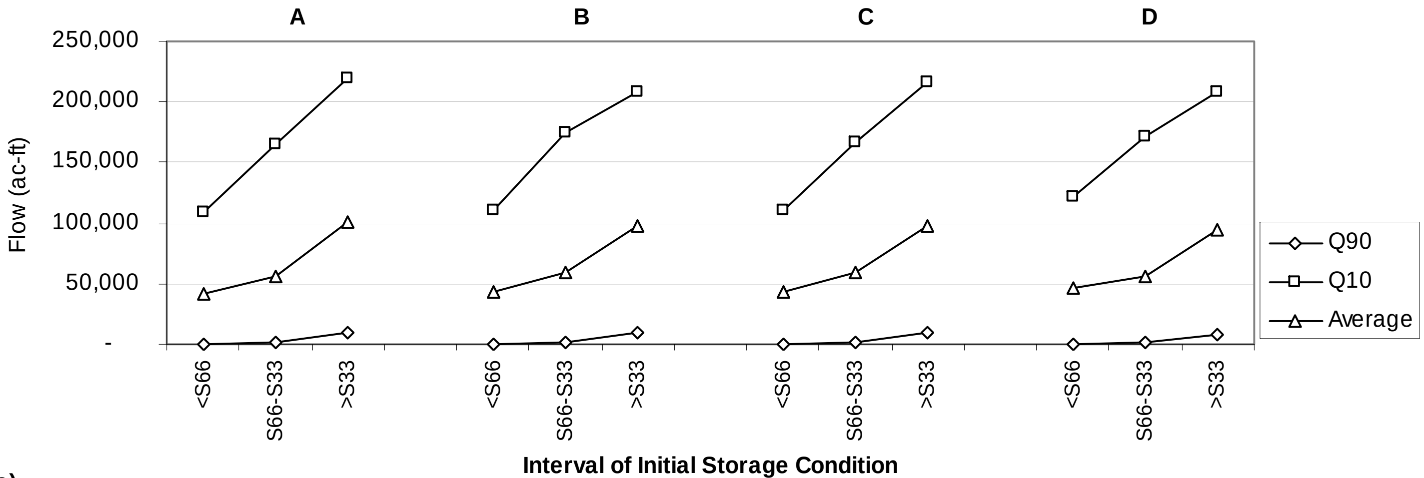
After having calculated correlation coefficients for each reservoir combination, the next step is to compute Conditional Frequency Duration Curves for each one of them. The objective is to visualize the behavior of each CFDC and be able to make a better judgment of each combination. In this case, the storage capacity was divided into 3 equal intervals, with low storage ranging from empty to S_{66}, medium storage ranging from S_{66}-S_{33} and High storage ranging from S_{33} to reservoir capacity. S_{66} refers to a value that is exceeded 66% of the time. The use of percentiles guarantees an adequate division of the reservoir storage capacity.

After building CFDC for each reservoir combination, a plot containing the average and the 90 and 10 percentiles of the CFDC is made. This plot allows visualizing the trend for each combination. It is desired to have a monotonous line extending from low storage ($<S_{66}$) to high storage ($>S_{33}$), than a fluctuating line. Figures 5.3 to 5.5 show these plots for both control points, 515531 and 515631.

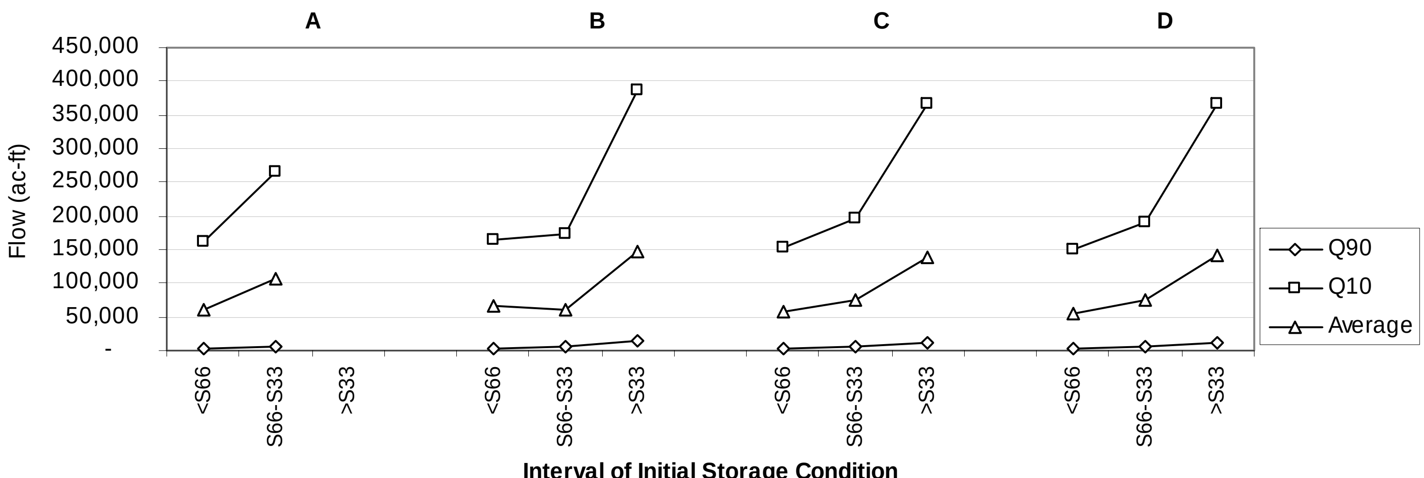
For the CFDC developed for 1 month, for control point 515531 all four combinations show good results, except for combination B, which doesn't show a linear behavior. For control point 515631, combination A has no elements for high storage, this is because the reservoir remains full more than 33% of the time and these elements will be included in the medium storage category. For combination B the naturalized flow decreased as storage increased, this behavior should not occur. Combinations C and D seem to be the ones with the most linear behavior.

For 3 months, for control point 515531, combinations C and D give the best results, while combination B decreases flow as storage increases. For control point 515631 again combinations C and D give the best results. For 6 months, for control point 515531, combination C gives very similar results for medium storage and high storage. For control point 515631, combination B decreases flow as storage increases and combinations C and D give good results.

Based on correlation analysis and a plot of the different CFDCs it is possible to select the most appropriate combination of reservoirs for a control point. For control point 515531 the appropriate combination is D, while for control point 515631 the appropriate combination is C.



(a)



(b)

FIGURE 5.3 CFDC of naturalized flows for 1 month at (a) control point 515531; and (b) control point 515631.

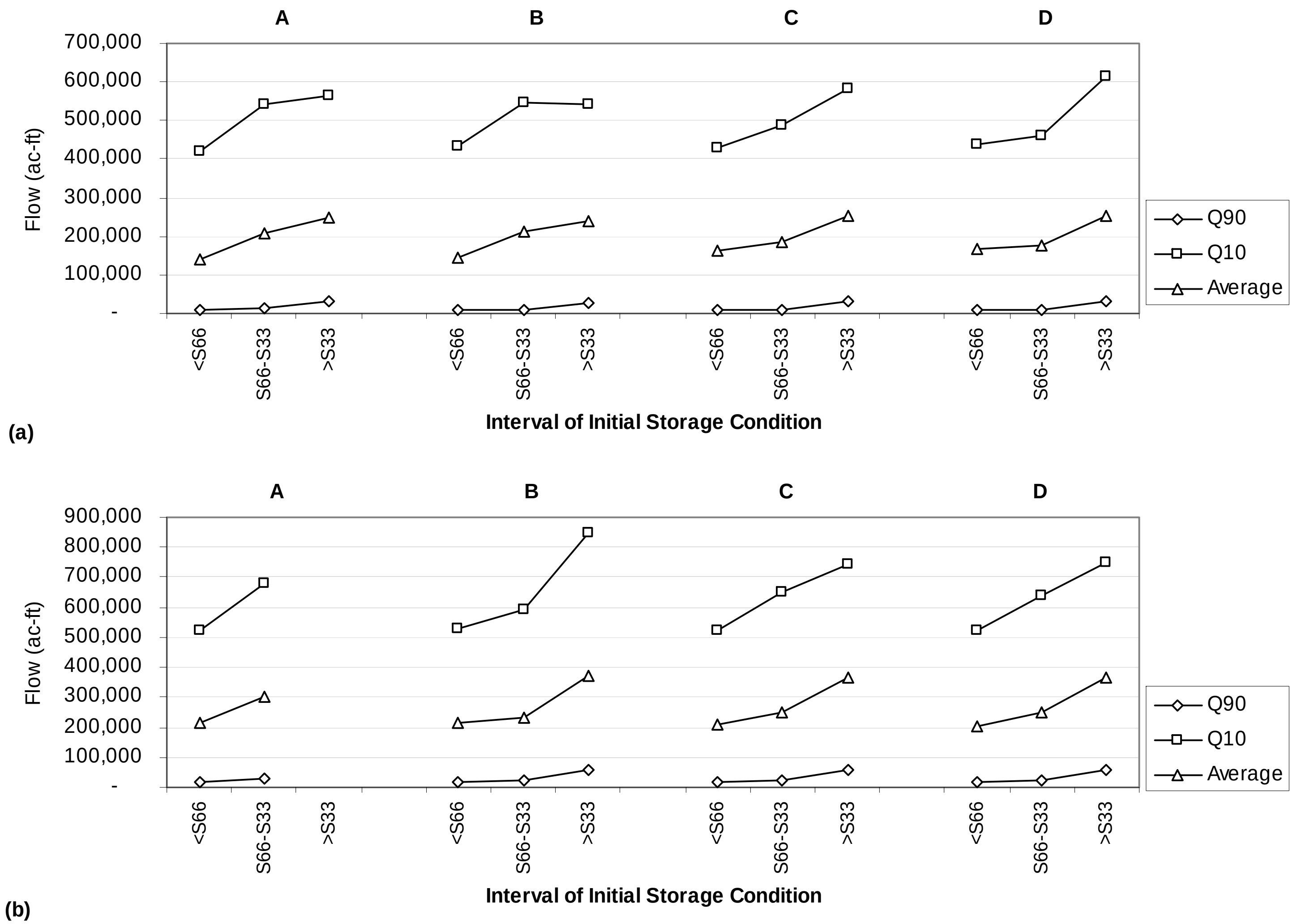


FIGURE 5.4 CFDC of naturalized flows for 3 months at (a) control point 515531; and (b) control point 515631.

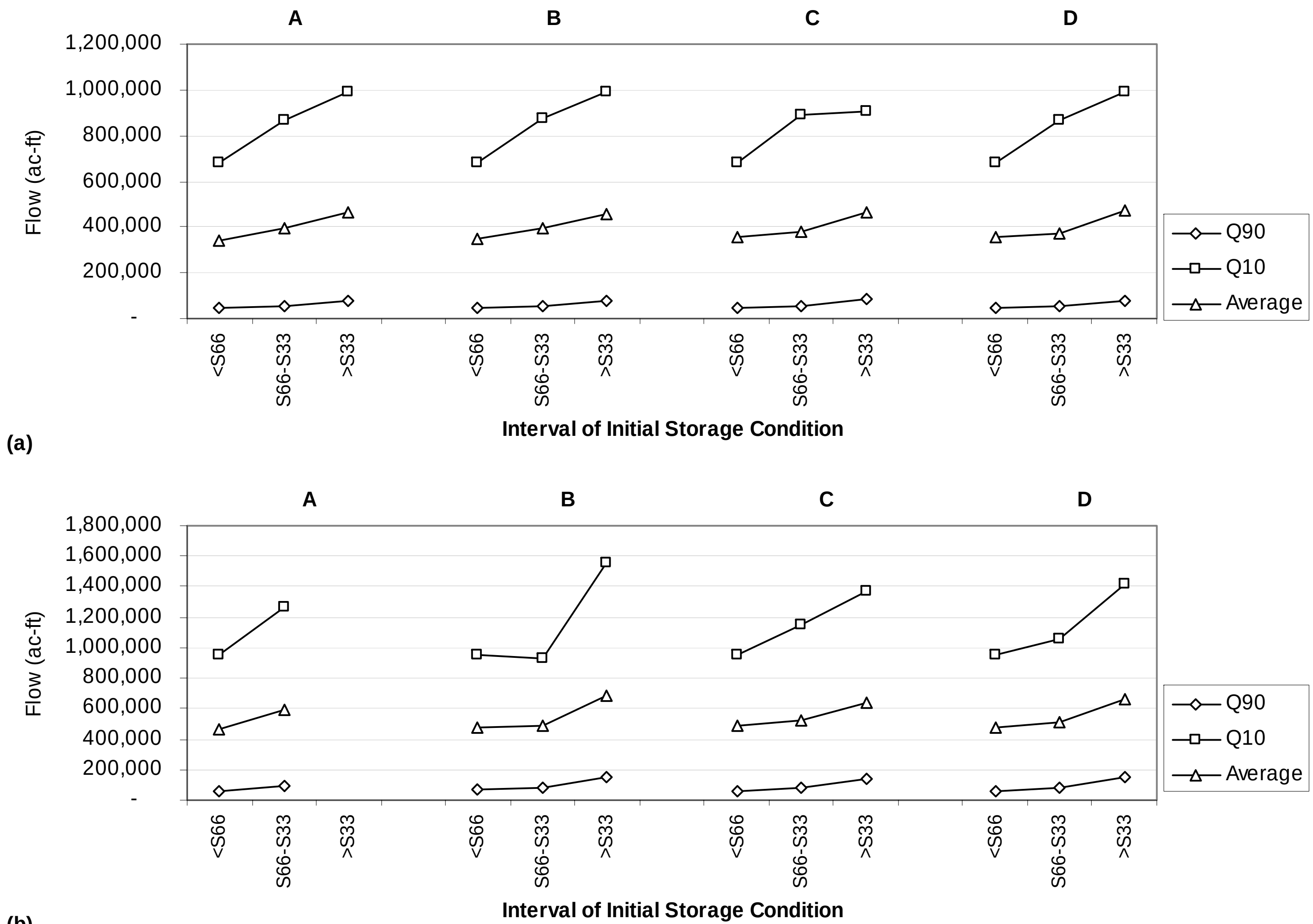


FIGURE 5.5 CFDC of naturalized flows for 6 months at (a) control point 515531; and (b) control point 515631.

Computation of conditional reliability

After the correct reservoir combination has been found, the corresponding CFDC is used to relate cumulated naturalized flows and probabilities of exceedance of a diversion/storage value. As described earlier, the model computes conditional reliability in two steps. The first step involves a regression analysis of the results obtained from the simulation, in order to establish a unique relation between naturalized flows and diversion/storage. It is possible that the results obtained from the regression analysis are not a good representation of the results; this is reflected by the R^2 coefficient that is printed in the output file. If the R^2 value is too low, then computed reliabilities will not be coherent with results for other periods or initial storage conditions.

Figure 5.6 shows an example where the regression analysis for a 58 year simulation does not give a good result; this may be more common for diversions than for storage reliabilities (since storage is calculated for the last period, while diversions are calculated over the period of analysis) and periods of analysis of 6 months or more. In this case it is recommended to use the equally likely methodology instead of the CFDC one.

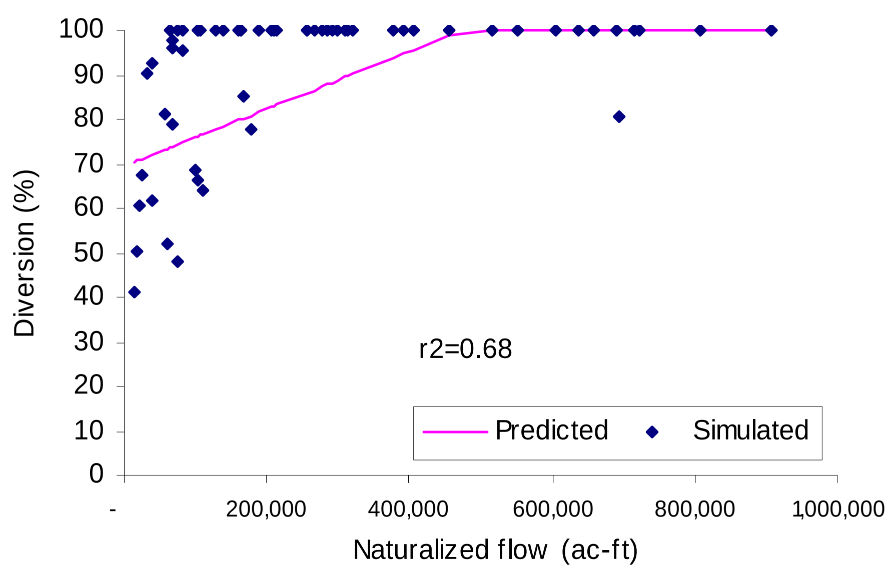


FIGURE 5.6 Flow-diversion regression for 6 months.

The second step involved in computing conditional reliabilities relates the flow-diversion/storage regression to the CFDC. This final step does not involve any complexities if the both, the CFDC and the flow-diversion/storage diversion have been developed following the stated procedures.

5.1.4 CFDC methodology example

The conditional reliability model using the CFDC methodology will be applied to Waco reservoir in the Brazos River Basin. An analysis will be performed for 1, 3 and 6 months into the future, with all simulations starting in January. The objective of this analysis is to estimate reliability values for diversion and storage at Lake Waco depending on the current storage in the reservoir.

The first step of the process is to perform the long term conventional WRAP simulation, using the WAM dataset for full authorization diversions. Cycling is performed in the simulation, by using BES option 4 in the JD record. Based on these results it is possible to perform a correlation analysis in order to find the best reservoir combination for control point 509431 (Lake Waco).

Tables 5.10 and 5.11 show linear and Spearman's correlation coefficients for control point 509431 and each one of the 12 main reservoir in the basin for 1, 3 and 6 months. For each period, the 4 highest coefficients are highlighted in red. Lake Waco and Belton are the reservoirs with the highest number of highlighted values, but Lake Waco has the highest total value when adding all coefficients. Belton, Stillhouse and Granger also have a significant number of highlighted values, mainly Spearman's coefficients. Some reservoirs like Proctor don't have any highlighted values for Spearman's coefficients, but all their linear coefficients are highlighted. Eleven reservoir combinations were chosen and are shown in Table 5.12. A correlation analysis was performed a second time for each reservoir combination, with results being showed in Tables 5.13 and 5.14.

TABLE 5.10 Linear Correlation Coefficients Between Reservoir Storage and Naturalized Flow for Control Point 509431

Period	Reservoir											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1	0.1169	**0.2068**	0.1819	0.1769	**0.1856**	**0.2192**	0.1670	0.1604	**0.1865**	0.1761	0.1404	0.1250
3	0.0995	**0.1896**	**0.1767**	**0.1699**	0.1335	**0.1902**	0.1565	0.1553	0.1663	0.1611	0.1040	0.0579
6	0.0742	**0.1705**	**0.1417**	0.1315	0.0419	0.1030	**0.1367**	**0.1381**	0.1110	0.1138	0.0298	-0.0334

TABLE 5.11 Spearman's Correlation Coefficients Between Reservoir Storage and Naturalized Flow for Control Point 509431

Period	Reservoir											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1	0.2009	0.2815	0.3135	0.3303	**0.3688**	**0.4111**	**0.3438**	0.3359	0.3172	**0.3709**	0.3150	0.3412
3	0.1267	0.2252	0.2452	0.2421	0.2507	**0.3226**	**0.2794**	**0.2619**	0.2615	**0.3141**	0.2330	0.2232
6	0.0782	0.1576	0.1550	0.1293	0.1063	0.1793	**0.1980**	**0.1798**	**0.1807**	**0.2193**	0.1206	0.0806

TABLE 5.12 Reservoir Combinations

Combination	Reservoirs		
A	LKWACO		
B	LKWACO	PROCTOR	
C	LKWACO	AQUILLA	
D	LKWACO	BELTON	
E	LKWACO	GRNGER	
F	LKWACO	PROCTOR	AQUILLA
G	LKWACO	PROCTOR	BELTON
H	LKWACO	PROCTOR	GRNGER
I	LKWACO	AQUILLA	BELTON
J	LKWACO	AQUILLA	GRNGER
K	LKWACO	BELTON	GRNGER

TABLE 5.13 Linear Correlation Coefficients for Different Reservoir Combinations at Control Point 509431

Period	Reservoir combination										
	A	B	C	D	E	F	G	H	I	J	K
1	**0.2192**	**0.2385**	0.2156	0.1867	0.2130	**0.2335**	0.1962	**0.2323**	0.1889	0.2121	0.1882
3	**0.1902**	**0.2102**	0.1807	0.1710	0.1874	**0.2000**	0.1797	**0.2063**	0.1703	0.1813	0.1723
6	0.1030	**0.1351**	0.0909	0.1327	0.1097	0.1201	**0.1418**	**0.1353**	0.1277	0.0996	**0.1326**

TABLE 5.14 Spearman's Correlation Coefficient for Different Reservoir Combinations at Control Point 509431

Period	Reservoir combination										
	A	B	C	D	E	F	G	H	I	J	K
1	0.4111	0.4189	0.4264	0.3829	**0.4290**	**0.4267**	0.3977	**0.4342**	0.3960	**0.4396**	0.3941
3	0.3226	**0.3316**	0.3246	0.3053	**0.3415**	0.3288	0.3187	**0.3460**	0.3097	**0.3387**	0.3141
6	0.1793	0.1990	0.1729	0.1997	**0.2028**	0.1885	**0.2117**	**0.2133**	0.1956	0.1916	**0.2053**

Again the four highest coefficients for each period are selected, with combination H having the highest number of highlighted values; this combination contains Lake Waco, Proctor and Granger reservoirs. When analyzing individual reservoirs, Proctor didn't have any Spearman's coefficients values selected, and Granger didn't have any linear coefficients selected, but when combining them with Lake Waco they gave the best correlation values. This suggests that not only reservoirs with the highest individual correlation coefficients should be considered, but also those with lower values.

Other combinations such as B and F gave good results and can also be applied in the model. Notice how combination A which only considers Lake Waco, didn't get selected. This also suggests that in some cases multiple reservoirs give a better correlation than single reservoirs.

Because it is easier to compare 6 combinations rather than 11, CFDC were built for 6 combinations, (A,B,E,F,H and J). Figures 5.7 to 5.9 compare these CFDC by plotting their 10 and 90 percentiles and the average values for each storage level. To the author's opinion, combinations F, H and J have a good behavior, so any of these combinations can be used, preferring H since it has the highest correlation. The reservoirs selected for the control point at Lake Waco are Lake Waco, Proctor and Granger reservoirs.

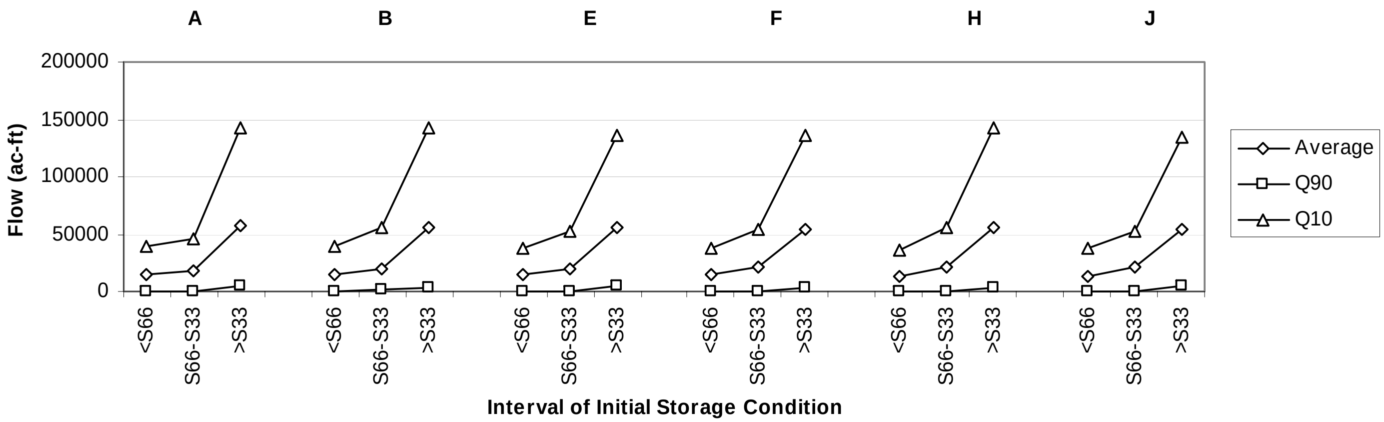


FIGURE 5.7 CFDC of naturalized flows for 1 month at Control Point 509431

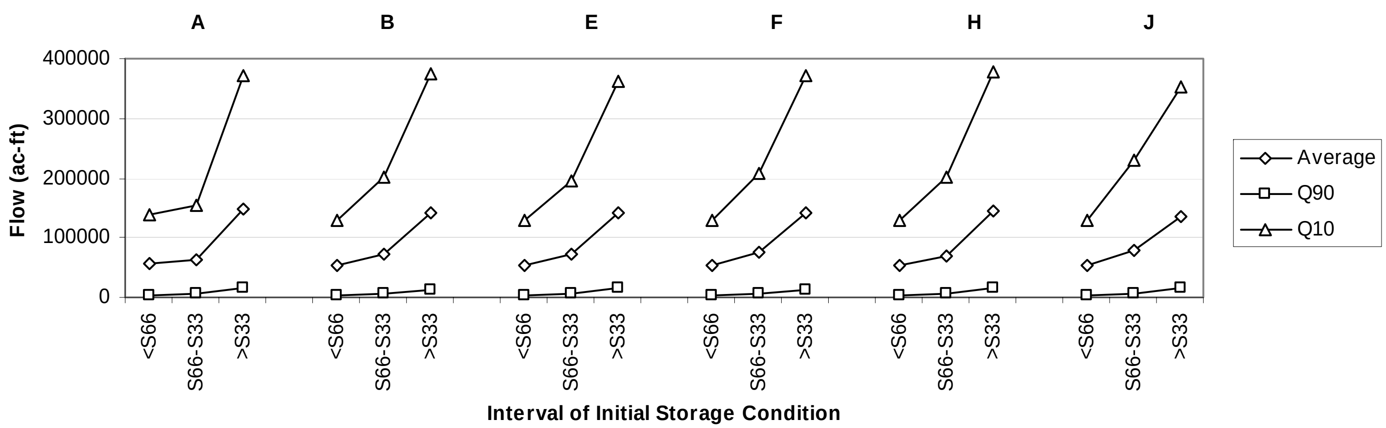


FIGURE 5.8 CFDC of naturalized flows for 3 months at Control Point 509431

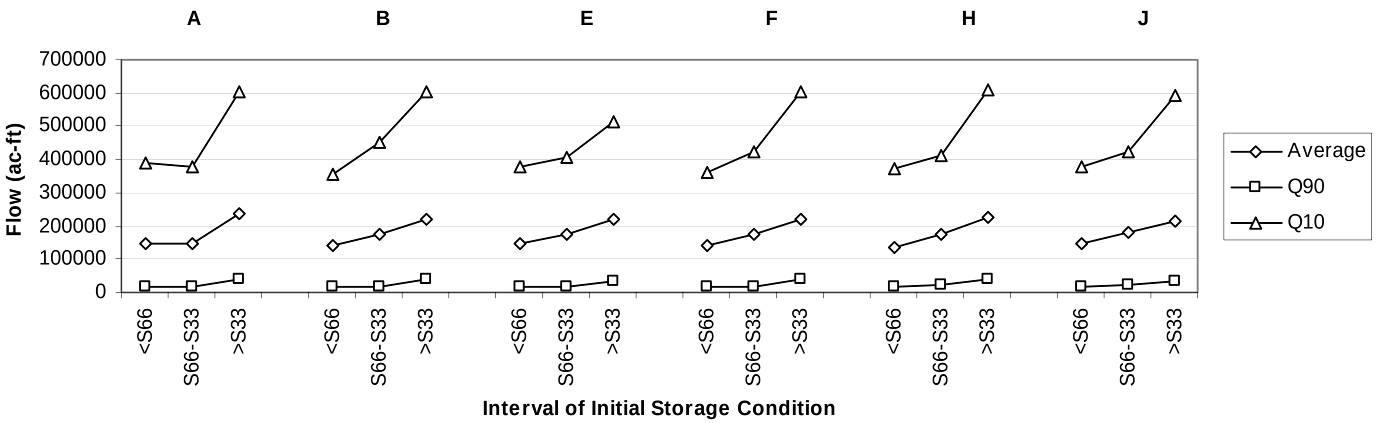


FIGURE 5.9 CFDC of naturalized flows for 6 months at Control Point 509431

Table 5.15 shows the CFDC for Lake Waco, for 1, 3 and 6 moths. Lake Waco is a reservoir that remains full or almost full, most of the time. Figure 5.10 shows the storage time series for Lake Waco and Table 5.16 shows the storage-frequency also for Lake Waco. 50% of the time, the reservoir is at least 92.5% full, 90% of the time it is 59% full and the mean storage is 85.8%. This is the reason why storage intervals for the CFDC are skewed to high storage values. Low, medium and high intervals correspond to 0-83%, 83%-96% and 96%-100% of capacity, respectively. Probabilities for low and medium storage are more similar than those corresponding to medium and high storages. For example, from the 3 months CFDC, the flow exceeded 50% of the time for medium storage conditions is 71% greater than the one for low storage conditions; while the corresponding one for a high storage condition is 264% greater than the one for medium storage conditions. This can be easily appreciated in Figure 5.11.

TABLE 5.15 CFDC for Control Point at Lake Waco for 1, 3 and 6 Months; Using Combination H

Period	Storage (ac-ft)	Mean	% of months equaling or exceeding total naturalized flow in table							
			100%	95%	90%	75%	50%	25%	10%	MAX
1	<= 262709.	13556	0	10	106	1238	4452	12918	35554	335074
	262709.- 305259.	20529	2	50	635	2482	7609	21604	55256	254184
	> 305259.	55516	7	1215	3907	11474	27751	71586	143046	530557
3	<= 262694.	53105	0	2066	3041	9702	22986	66546	128675	671365
	262694.- 305259.	70841	130	4403	6742	14707	34270	87986	202393	543176
	> 305259.	144306	524	9035	15687	31478	92554	192616	376796	1039415
6	<= 262221.	136488	3167	10300	14526	30182	75248	180712	371544	720883
	262221.- 305259.	172292	3788	14589	20782	44180	104257	255048	409771	862971
	> 305259.	228611	2693	26388	37920	66856	150518	297453	609464	1296383

Combination H Lake Waco, Proctor and Granger Tot Storage: 316962

TABLE 5.16 Storage-Frequency for Lake Waco

Mean	% of months with storage equaling or exceeding % of storage capacities shown in table									
	100%	99%	98%	95%	90%	75%	60%	50%	40%	25%	10%
85.8	20.2	27.0	33.8	47.8	58.8	78.3	87.3	92.5	97.2	100.0	100.0

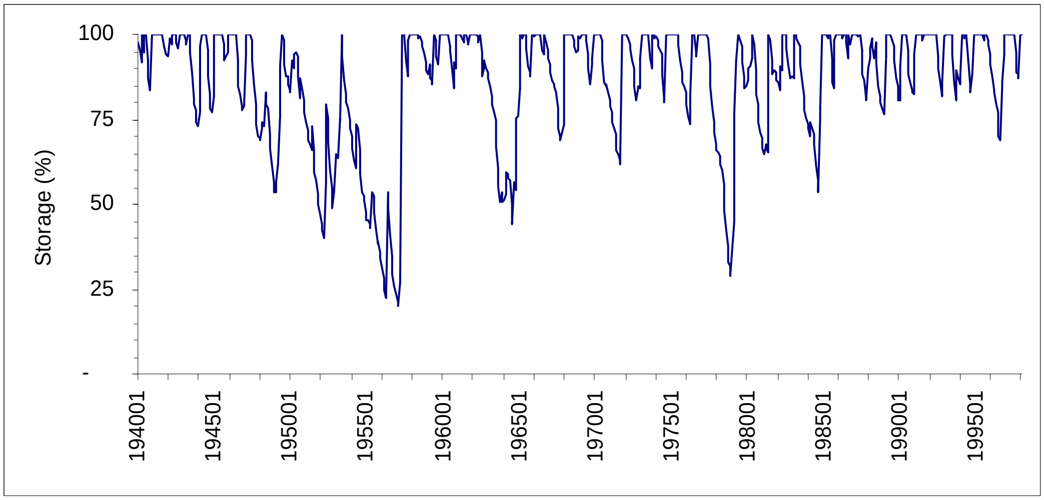


FIGURE 5.10 Storage time series for Lake Waco. 1940-1997.

Eight different conditions were modeled, with Lake Waco and Proctor reservoirs starting empty, at 10%, 25%, 50%, 75%, 85, 90% and 98% of their capacities. Figures 5.12 to 5.14 show the simulation results for the first condition for 1, 3 and 6 months including the regression analysis for both, storage and diversions. Reliability curves for storage and diversion are also included in these figures.

Notice how in all the cases, except for the 6 months diversion analysis, the regression has a high R^2 value. In the case of 1 month analysis, the regression fit is perfect, since there is a single flow value. The goodness of fit decreases as the period of analysis increases, with more impact on diversions than storages. Notice how in Figure 5.12b some small flows have a higher diversion than other larger flows; in Figure 5.13b this difference is greater and the R^2 value drops to 0.68, simulation results for low flows are so scattered that it is not possible to fit a regression through them, while in Figure 5.12a, the R^2 is close to 1.

Diversion reliabilities for all other conditions were 100%, while storage reliabilities vary significantly. Figures showing simulation results for the remaining conditions are shown in Appendix A, Figures A.1-A.21.

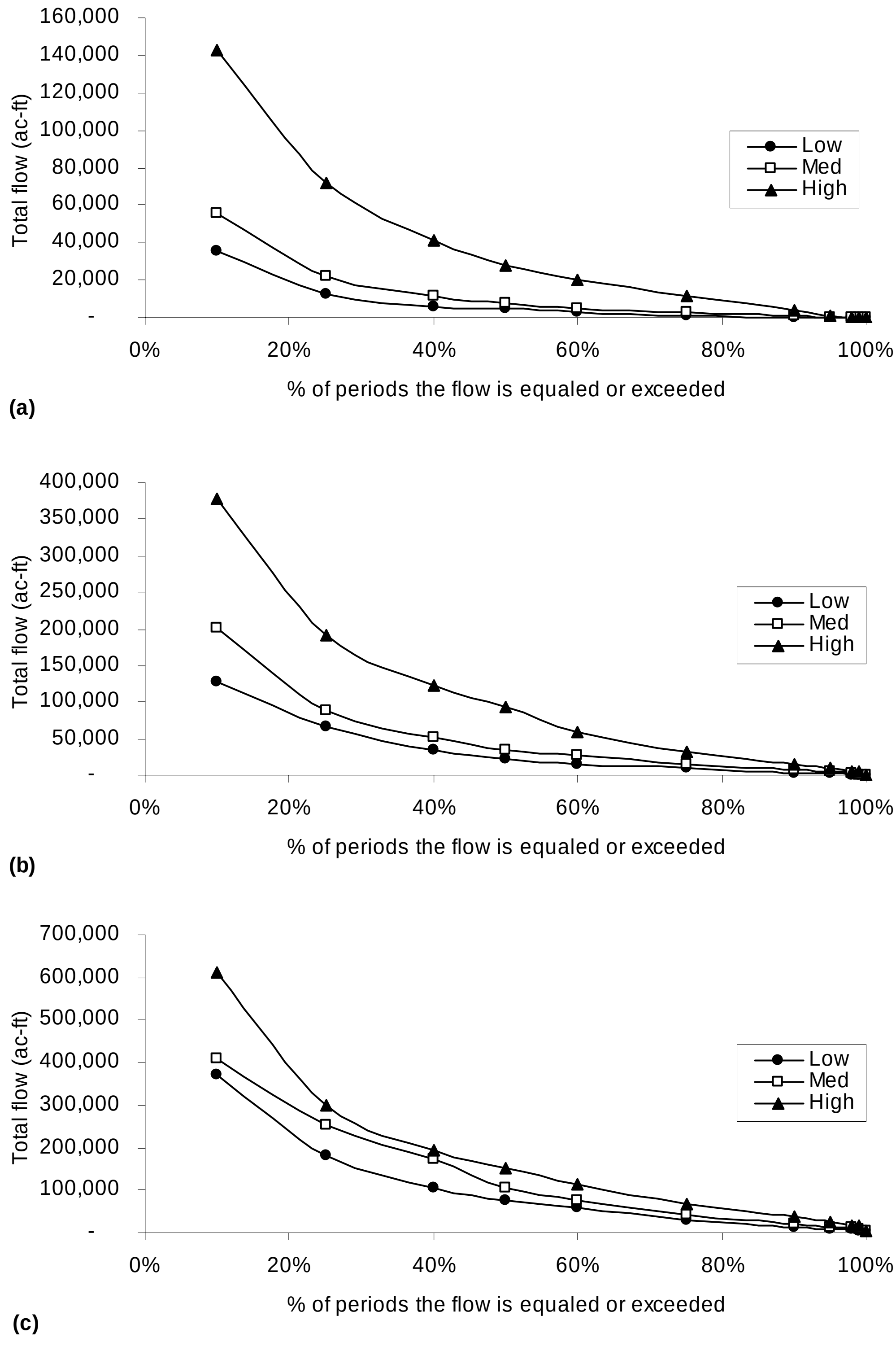


FIGURE 5.11 CFDC for 1, 3 and 6 months for Lake Waco.

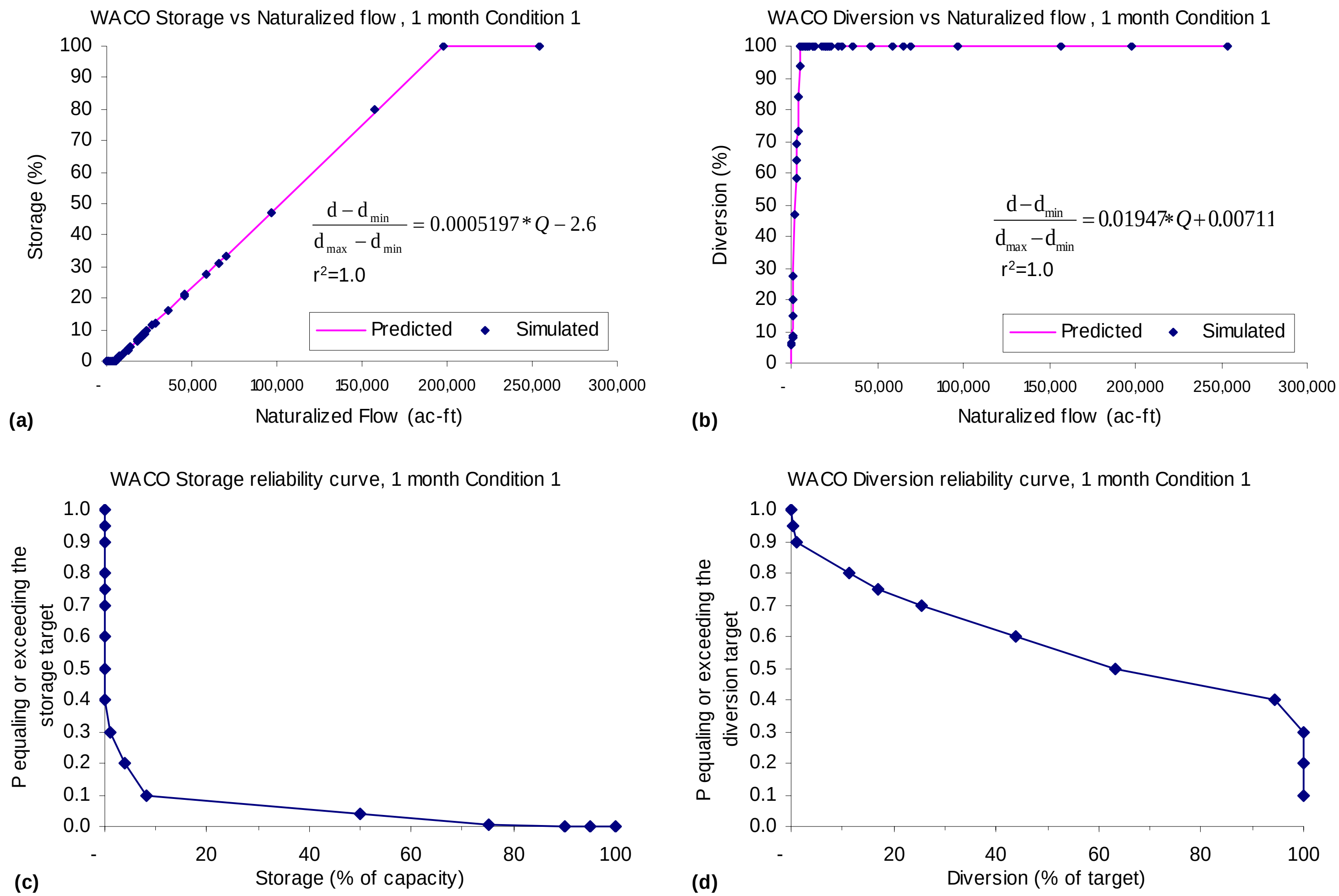


FIGURE 5.12 Condition 1 simulation results for Lake Waco for 1 month; (a) flow-storage regression; (b) flow-diversion regression; (c) storage reliability curve; (d) diversion reliability curve.

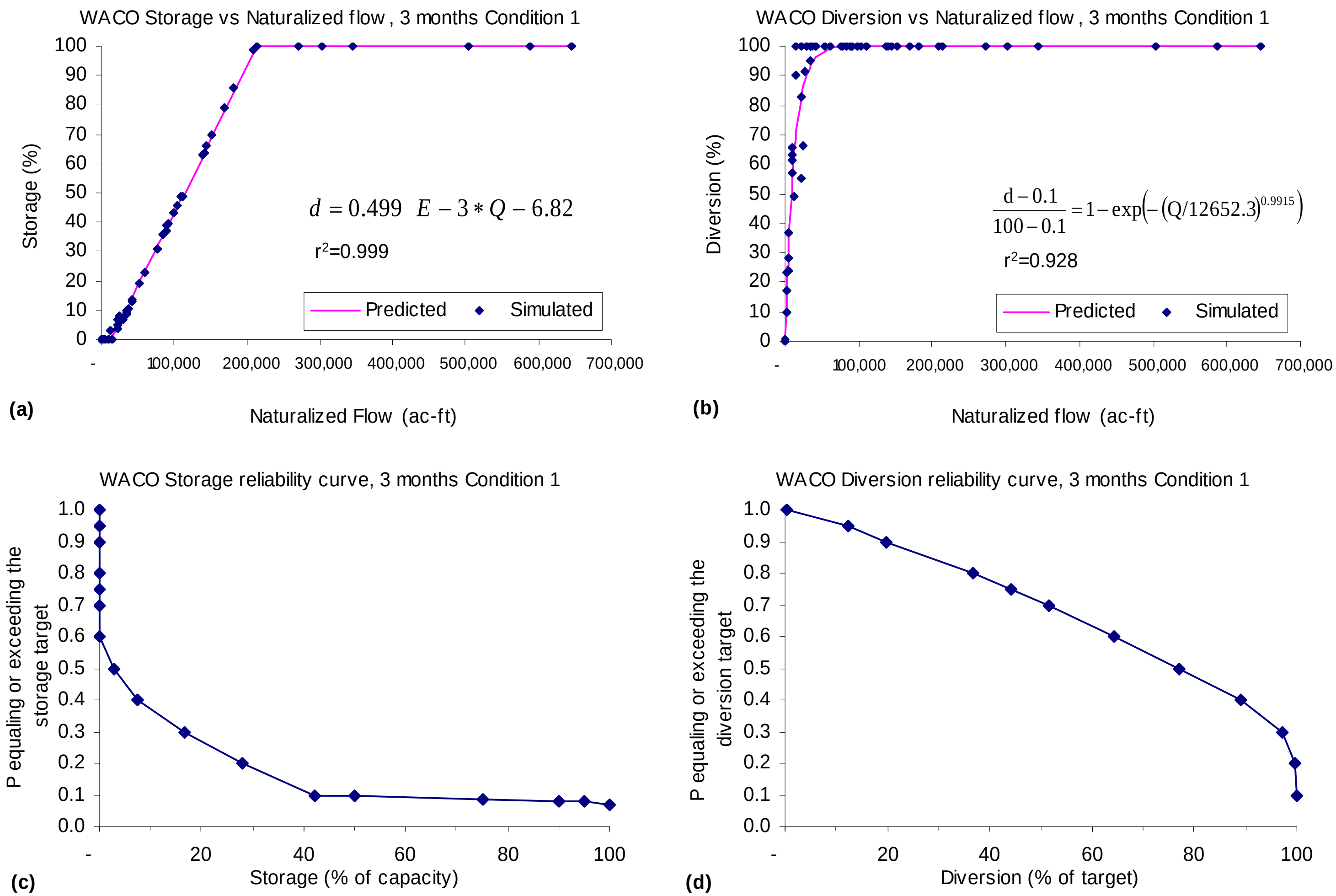


FIGURE 5.13 Condition 1 simulation results for Lake Waco for 3 months; (a) flow-storage regression; (b) flow-diversion regression; (c) storage reliability curve; (d) diversion reliability curve.

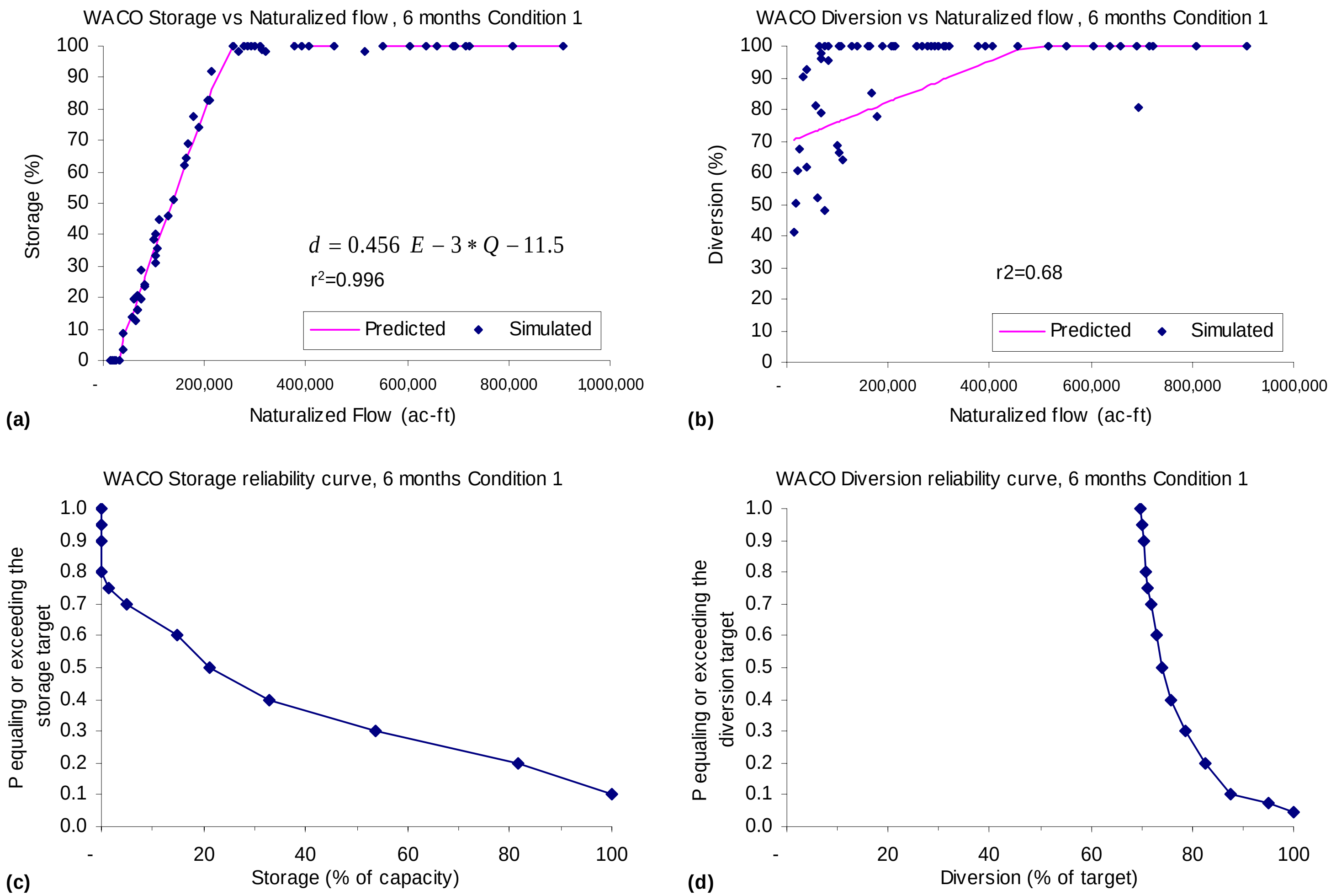


FIGURE 5.14 Condition 1 simulation results for Lake Waco for 6 months; (a) flow-storage regression; (b) flow-diversion regression; (c) storage reliability curve; (d) diversion reliability curve.

Detailed conditional reliability results for Storage and Diversions at Lake Waco are shown in Tables 5.17 and 5.18. When analyzing storage reliabilities, in general they are consistent (reliabilities increase as initial storage increases), but there are some exceptions. When looking at the 6 months reliabilities, the probability of the reservoir being full at the end of the period for an initial storage of 10%, is less than the one obtained when the reservoir starts with 25% of its capacity. This can be explained by the type of regression being selected to build the flow-storage relationship; the S-curve regression is very sensitive when reaching 100% of the target, this can impact the probability of the reservoir being full or the probability of meeting totally demand targets, but reliabilities for other fractions of the target are not significantly affected.

Another inconsistency was found when comparing reliability estimates for 1 and 3 months between simulations starting with 90% and 98% of the reservoir capacity. There is a big jump on reliabilities when starting with 98% although the difference in initial storage is of only 8%. The CFDC for low storage values applies to the first five conditions, the one for medium storages applies to the sixth and seventh conditions and the one for high storages applies to the last condition. So the medium storage condition applies to an initial storage of 90% and the high storage condition applies to a 98% one. From Figures A16a, A17a, A19a, A20a it is possible to find the minimum flow required to meet 100% of the storage capacity; for 90% of initial storage, the minimum flow is 27,000 ac-ft and 41,000 ac-ft for 1 and 3 months respectively; for 98% of initial storage, the minimum flow is 12,000 ac-ft for 1 month and 33,000 ac-ft for 3 months. These results seem correct, but when calculating their respective exceedance probability is when they become odd. From Table 5.15 it is possible to find the respective exceedance probabilities for each flow; for 90% initial storage a flow of 27,000 ac-ft will be exceeded 23% over the next month, and a flow of 42,000 ac-ft will be exceeded 46% over the next 3 months; for the 98% initial storage, a flow of 12,000 ac-ft over the first month will be exceeded 74% of the time and a flow of 33,000 ac-ft will be exceeded also 74% of the time over the next 3 months. This is why storage reliabilities are 22% and 74% for the first month if starting with Lake Waco at 90% or 98% of its capacity respectively, and 46% and 74% over the next 3 months for the same initial storage levels.

TABLE 5.17 Conditional Reliability Results for Storage at Lake Waco

Period	Initial	Expected Values for			Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table											
	Storage	Drawdown (Ac-ft)	P-full Rel (%)	Storage Rel (%)	100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	173543	4.81	9.60	0	0	0	0	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.17
	10%	157364	4.82	18.10	0	0	0	0.07	0.07	0.07	0.08	0.09	0.09	0.10	0.17	0.43
	25%	130359	6.12	32.10	0	0.06	0.07	0.08	0.08	0.08	0.09	0.09	0.11	0.24	1	1
	50%	85892	6.19	55.30	0	0.08	0.09	0.09	0.09	0.10	0.17	0.41	1	1	1	1
	75%	42505	9.28	77.90	0.09	0.10	0.11	0.23	0.39	1	1	1	1	1	1	1
	85%	21825	18.84	88.60	0.19	0.23	0.33	1	1	1	1	1	1	1	1	1
	90%	14282	22.75	92.60	0.23	0.33	0.55	1	1	1	1	1	1	1	1	1
	98%	1348	74.07	99.30	0.74	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	153785	7.93	19.90	0.08	0.09	0.09	0.09	0.09	0.10	0.11	0.14	0.18	0.24	0.31	0.41
	10%	140655	8.60	26.80	0.09	0.09	0.09	0.10	0.10	0.11	0.14	0.18	0.23	0.30	0.40	0.57
	25%	115106	9.28	40.10	0.09	0.10	0.10	0.12	0.14	0.16	0.21	0.26	0.35	0.47	0.79	1
	50%	73044	10.12	62.00	0.10	0.16	0.18	0.23	0.26	0.30	0.39	0.55	1	1	1	1
	75%	35082	22.79	81.70	0.23	0.29	0.34	0.45	0.54	0.76	1	1	1	1	1	1
	85%	16662	39.38	91.30	0.39	0.47	0.56	0.85	1	1	1	1	1	1	1	1
	90%	11232	45.92	94.20	0.46	0.57	0.69	1	1	1	1	1	1	1	1	1
	98%	2316	74.38	98.80	0.74	0.88	1	1	1	1	1	1	1	1	1	1
6 months	0%	117813	9.40	38.70	0.09	0.18	0.21	0.24	0.25	0.27	0.31	0.35	0.39	0.44	0.51	0.65
	10%	112431	13.64	41.50	0.14	0.22	0.24	0.28	0.30	0.31	0.35	0.38	0.41	0.47	0.54	0.66
	25%	91619	11.98	52.30	0.12	0.22	0.25	0.31	0.34	0.36	0.40	0.45	0.52	0.63	0.73	1
	50%	60460	14.76	68.50	0.15	0.25	0.31	0.38	0.42	0.46	0.57	0.68	0.82	1	1	1
	75%	30334	20.79	84.20	0.21	0.38	0.45	0.62	0.68	0.73	0.95	1	1	1	1	1
	85%	15212	31.39	92.10	0.31	0.54	0.66	0.83	0.91	1	1	1	1	1	1	1
	90%	12936	27.76	93.30	0.28	0.55	0.69	0.90	1	1	1	1	1	1	1	1
	98%	6393	22.92	96.70	0.23	0.72	0.92	1	1	1	1	1	1	1	1	1

TABLE 5.18 Conditional Reliability Results for Diversions at Lake Waco

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table 100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	5137.5	1815.1	40.8	64.7	0.41	0.46	0.49	0.52	0.54	0.55	0.58	0.63	0.67	0.72	0.78	0.85
	10%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	15504.0	4274.6	20.3	72.4	0.20	0.38	0.45	0.53	0.56	0.59	0.69	0.77	0.82	0.87	0.92	0.96
	10%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
6 months	0%	35505.2	7737	6.2	78.2	0.06	0.09	0.14	0.28	0.46	0.96	1	1	1	1	1	1
	10%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1

Storage reliability results over 6 months for conditions starting with 90 and 98% of storage capacity are smaller than the reliability obtained for a 85% of initial storage. This is due to the lack of accuracy of the regression for the last two conditions. The R^2 coefficient for a simulation starting with 85% of the storage capacity is 0.90, while for 90% is 0.87 and for 98% is 0.76. Since the 100% reliability is very sensitive to the regression results, this is why the reliability instead of increase with initial storage, decreases.

For low storage conditions, storage reliabilities increase with time, but for medium to high storage conditions, storage reliabilities increase for 3 months and then decrease for 6 months.

The analysis for diversions is very limited, since reliabilities for conditions 2 and above are always 100%. When simulations start with reservoirs empty, diversion reliabilities decrease with time, but volume reliability increases. Also, for high fractions of the diversion target, diversion reliabilities decrease with time, while for fractions smaller than 75% of the target, reliabilities increase with time as shown in Figure 5.15.

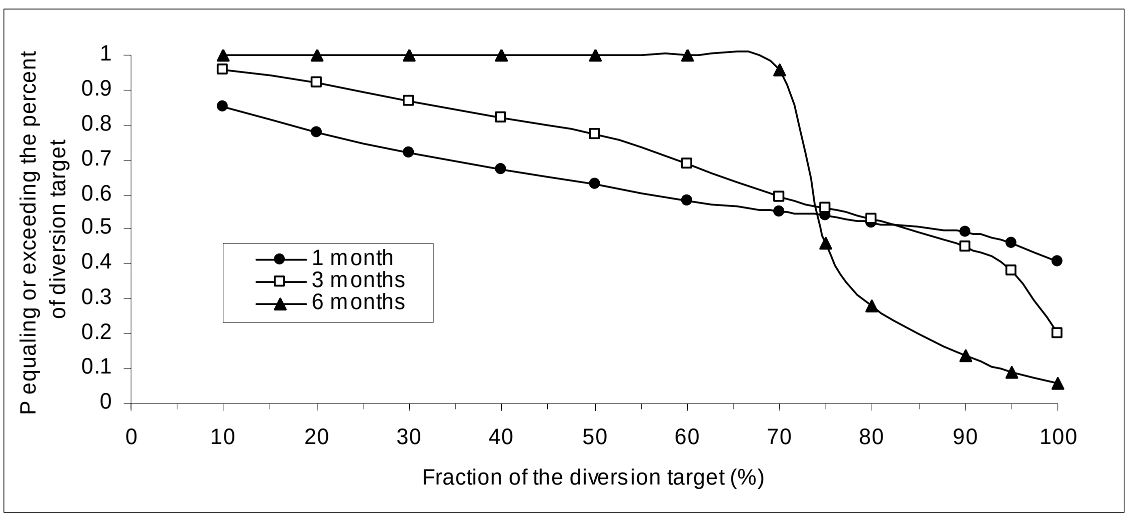


FIGURE 5.15 Diversion reliability variation with time for zero initial storage.

The same conditional reliability analysis was done using 2 more CFDC, using combinations B and F from Table 5.12. These combinations had the second and third highest correlation values. Storage and diversion reliability tables are shown in Tables

A.1 – A.4. Figure 5.16 shows a comparison for the 3 months storage reliabilities obtained with 3 different CFDC with reservoirs starting 50% full. All three combinations give almost the same reliabilities. This may be caused by the high storage-flow correlation for all combinations.

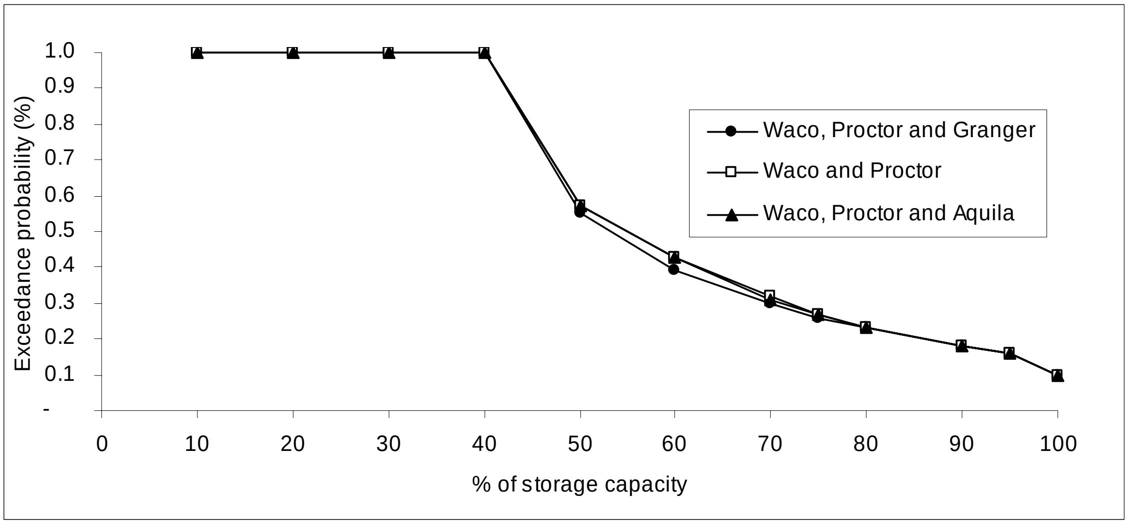


FIGURE 5.16 3 months conditional reliability for storage at Lake Waco starting with 50% of storage capacity, and 3 different reservoir combinations.

A comparison of the different probabilities of having the reservoir full at the end of the next 1, 3 and 6 moths for the 3 different reservoir combinations is shown in Figure 5.17. Notice that within the same period of analysis, all 3 combinations give almost the same result, once more; this is due to the high storage-flow correlation of all 3 combinations. Also notice that for 6 months, for initial storages of 90 and 98%, storage reliabilities decrease instead of increasing.

If a combination with a lower correlation, but with still reasonable results is used (combination A) then as shown in Figure 5.18, combination A assigns lower probabilities to high initial storage conditions, in some cases a difference as high as 10% is encountered. For lower initial storage conditions, reliabilities are about the same. Tables A.5 and A.6 show detailed results.

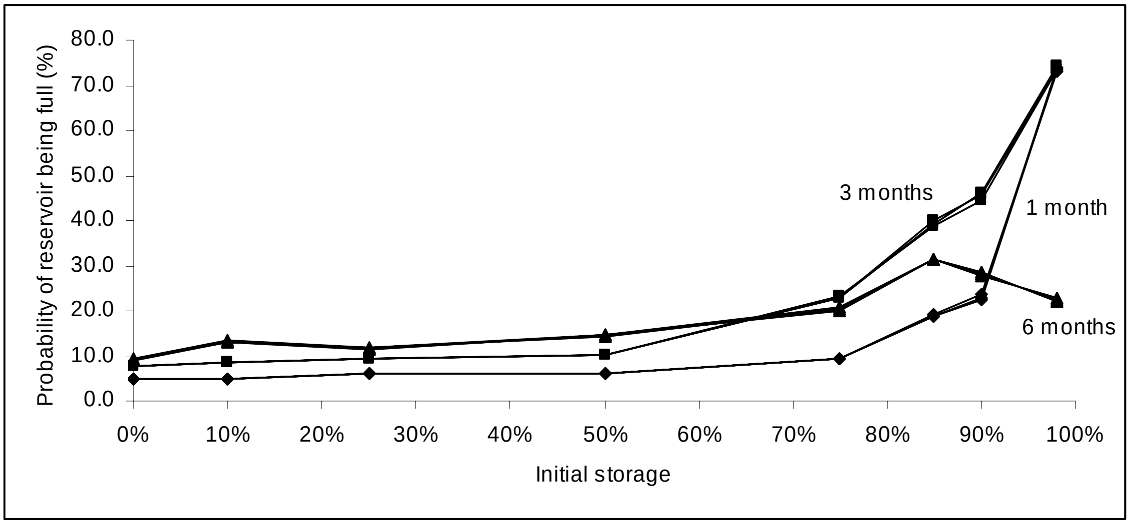


FIGURE 5.17 Probabilities of Lake Waco being full over the next 1, 3 and 6 months for 3 different combinations.

Comparison of results with the equally likely approach

A comparison between the equally likely reliabilities and the CFDC reliabilities is shown in Figure 5.19. It can be seen that for low initial storage conditions, the equally likely approach produces higher reliabilities than the ones obtained from the CFDC. This is because under low storage conditions, higher flows have lower probabilities of occurrence and low flows are more likely to occur. As the initial storage is increased, the reliabilities obtained with the CFDC approach increase and eventually exceed the equally likely reliability values, since with high storage conditions high flows are more likely to occur.

When the initial simulation storage is zero, differences between equally likely and CFDC reliabilities are as high as 20%. This difference decreases as the initial simulation storage increases. Tables A.7-A.8 show results for an equally likely simulation.

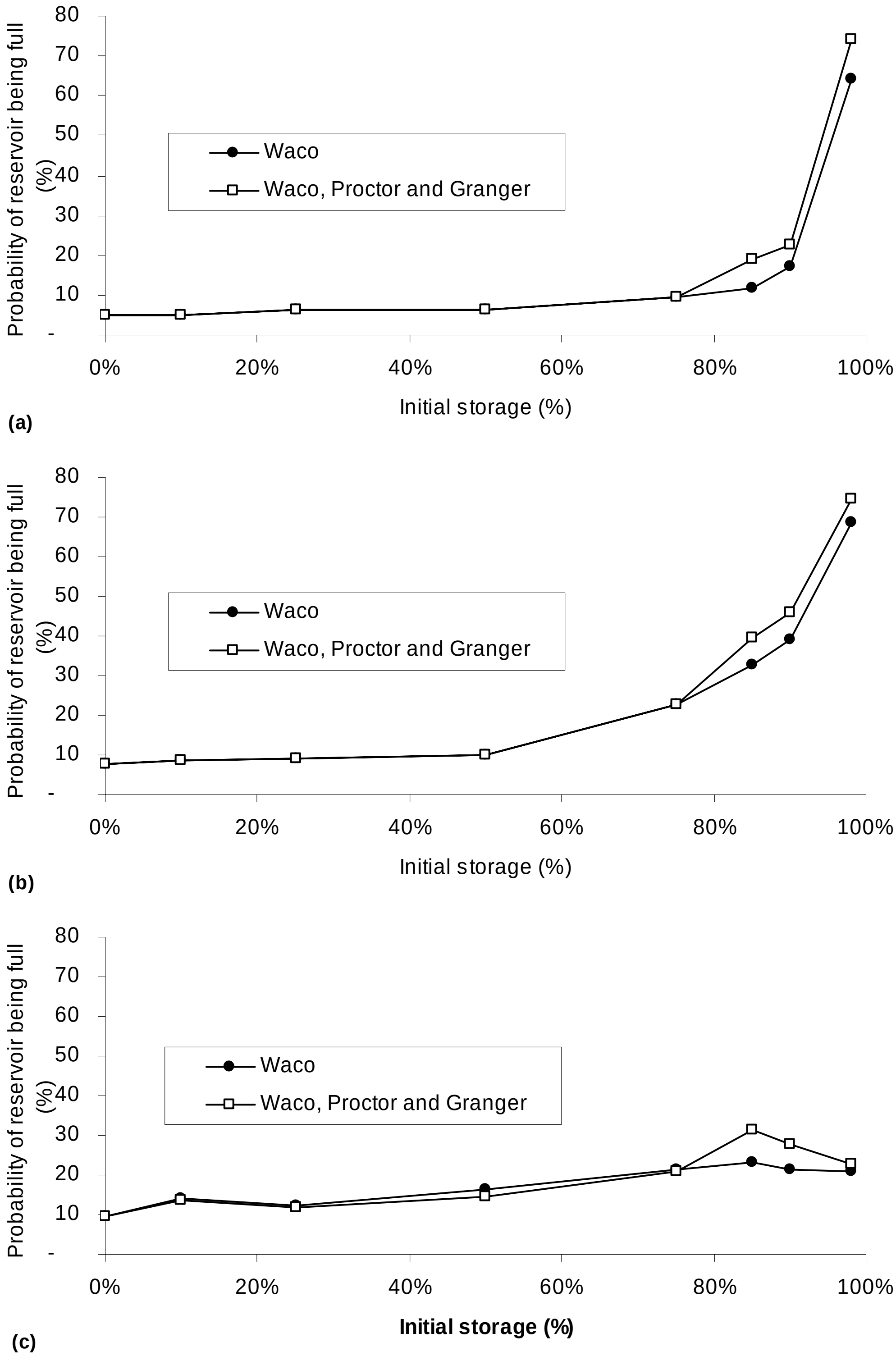


FIGURE 5.18 Probabilities of Lake Waco being full for two different reservoir combinations; (a) at 1 month; (b) at 3 moths; (c) at 6 months.

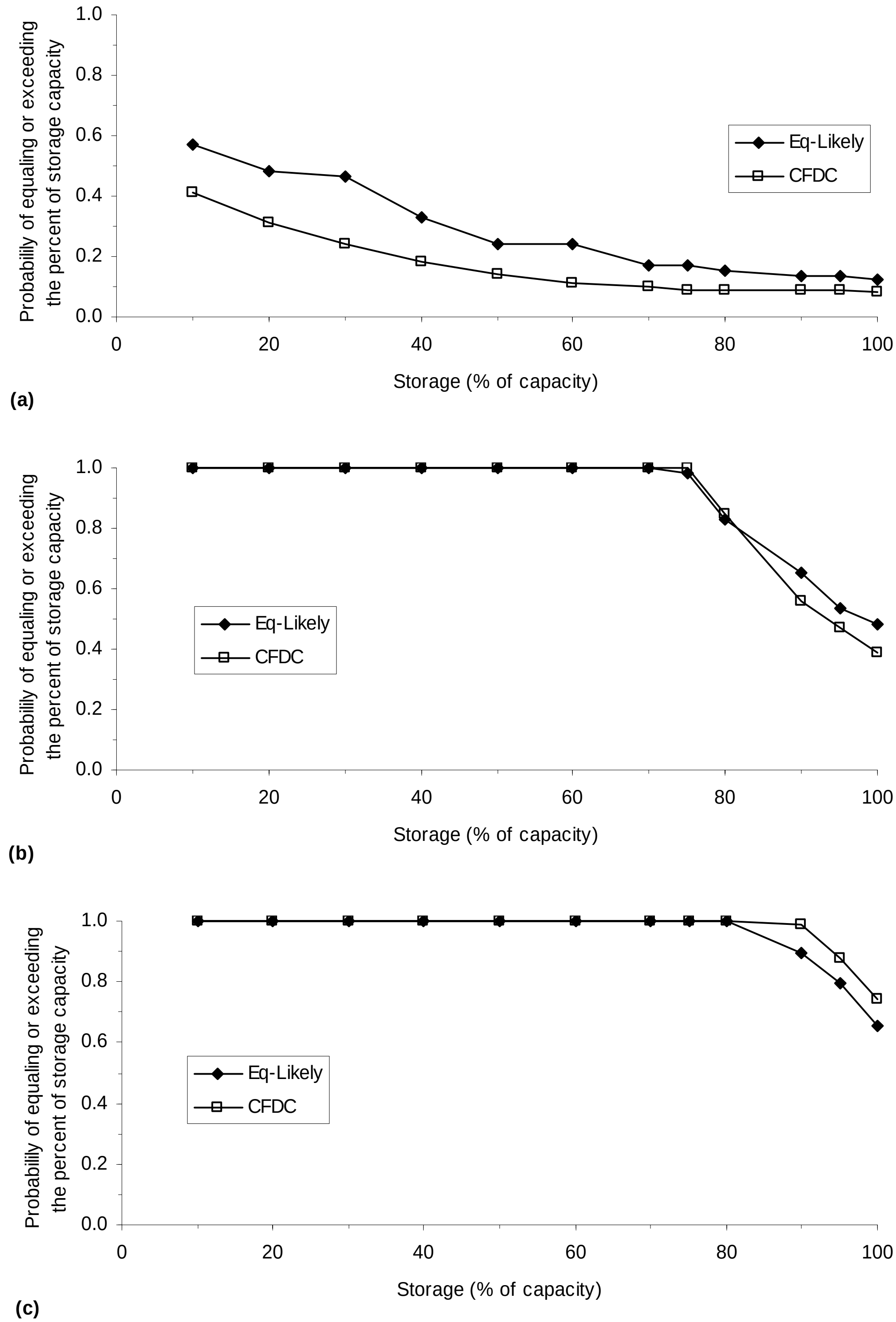


FIGURE 5.19 Comparison between the CFDC model and the Equally Likely Model for initial storages equal to: (a) 0%, (b) 85% and (c) 98%.

5.2 STORAGE FLOW FREQUENCY TECHNIQUE

5.2.1 Description of the model

The Storage Flow Frequency (SFF) methodology is similar to the CFDC one, in the sense that it divides a long term simulation into multiple short sequences, but the way probabilities are assigned to each sequence is completely different. Detailed description of the procedures followed by the model are described in Wurbs et al. (2004), a brief description is given next.

Probabilities of occurrence for each sequence are based on a relationship between preceding reservoir storage volume and the naturalized streamflows volume during the following specified number of months. Probabilities are assigned in two steps:

- A storage-Flow frequency array is developed from sequences of naturalized flows and preceding storage read from a long term simulation.
- The array of probabilities of occurrence for each sequence is developed from the naturalized flow volumes for each simulation sequence obtained from a CRM simulation for a given initial storage condition and combining it with the SFF array developed previously.

Relationship between naturalized streamflow and preceding storage

The SFF option to assign probabilities to each sequence is based on the relationship between storage-flows and frequency. A variable storing the ratio between flows and expected flows, measures the deviation of the flow volume from the expected value of the flow volume, depending on initial storage.

Four different regression equations can be used to relate naturalized flow volume and preceding storage volume, these are: exponential, linear, power and combined; with the exponential being the default option. In order to avoid prediction of negative flows for low storage volumes, an option to force the intercept of a regression to be zero is added; this option only applies to the linear and the combined regressions.

Another option available to the user is to establish upper and lower limits for storage volumes to be considered when applying a regression.

After reading the initial storage volumes and naturalized flow volumes from the long term simulation, the selected regression is applied and its coefficients representing the relationship between storage and flows are obtained. It is expected that flow volumes increase as storage increases, but if flows and storage values are very scattered, it is possible that the regression coefficients predict an inverse behavior. The user should pay attention to these results, and in case of having decreasing values of flows as the storage increases, then the intervals used to apply the regression should be modified.

The expected value of flow conditioned on storage is computed for each simulation sequence using the derived regression coefficients, and the corresponding values of the ratio between flow and expected flow are determined.

Storage-Flow-Frequency relationship

As with the CFDC methodology, the SFF option is also based on the correlation between future streamflows with preceding storage content. If a reservoir has low storage, it is because of dry conditions in the previous months and it is more likely that dry conditions will continue in the future. While if a reservoir is full, it is because wet conditions in the past and it is more likely that wet conditions will continue in the future. Reservoir storage contents are dependent upon flows in preceding months and if flows are correlated, then flows in future months are dependent with flows on previous months.

The SFF relationship is a two dimensional array that assigns exceedance probabilities to the streamflow sequences, based on the likelihood of departures of flow volumes from those expected based on the relation of flow with preceding storage. The exceedance probability can be assigned based on applying either the Weibull or Log-Normal probability distributions.

Incremental Probability array for the CRM simulation sequences

Once the SFF array has been created, it is necessary to assign incremental probabilities to each simulation sequence from a CRM simulation. The procedure used is as follows:

- The naturalized flows in each month of the sequences are read from the CRM output.
- Initial storages are read for the pertinent reservoirs
- Initial storage at specified reservoirs or control points are cumulated to obtain the total initial storage amounts. Naturalized flows over the specified months are also summed to obtain the total flow amounts for each sequence.
- The expected flow value is calculated based on either regression coefficients computed when developing the SFF relationship or user defined values.
- Ratios between cumulated flows and expected flow values are determined.
- The ratios obtained are linearly interpolated within the SFF array, to obtain an exceedance frequency for each ratio (sequence).
- The ratios are ranked in order and their corresponding exceedance frequency is converted into incremental probabilities. This incremental probability is computed based on the half-way points between the exceedance probabilities of that ratio and the next larger ratio and next smaller ratio.

As a result of this process, incremental probabilities are assigned to each CRM sequence, the total sum of these incremental probabilities is 1. These probabilities are the ones used to calculate reliabilities or frequencies.

Reliability and frequency analysis

Reliability and frequency analyses are performed by applying a weight to each one of the many sequences in a CRM simulation, this weight is the incremental probability for each sequence. With it, it is possible to reflect the fact that some sequences are more likely to occur than others.

5.2.2 Methodologies to apply the model

Procedures and recommendations that should be taken when applying the model are described in the following sections.

Effect of initial storage in a long term simulation

As with the CFDC option, it is recommended to use cycling in order to reduce the effect of the initial storage in the simulation. This will convert the storage levels at the end of the simulation into initial storage levels for the second simulation.

Performing a Conditional Reliability simulation

When performing a conditional reliability simulation, the DAT file has to be modified by adding a CR record with the specifications for the simulation. Cycling should not be used on this kind of simulations, since the initial storage condition would be modified and results would be meaningless.

If there is more than one period of analysis, it is recommended to perform separate simulations for each period, since reliabilities can only be calculated considering all the months in the simulation or a specific month, and it would not be possible to calculate a diversion reliability during the first three months on a six months simulation.

Control Points and reservoirs used to develop SFF

In order to determine the control points to be used when developing the SFF, it is necessary to have full knowledge of the operating policies concerning the study area. In most cases, when performing a conditional reliability analysis in a reservoir, the control point used to consider naturalized flows should be the one where the reservoir is located. However, depending on the operating policies more than one control point can be taken into account. For example, in the Brazos River Basin, Allens Creek reservoir is a reservoir planned to be constructed in the next years, it is located in the lower basin, close to Richmond. This reservoir refills with water from Allens Creek (292531) and water pumped from the Brazos River at control point 292504. This is a case when storage in a reservoir may be correlated to the streamflow in more than one control point. Figure 5.20 shows a map with the location of the reservoir and the two control points.

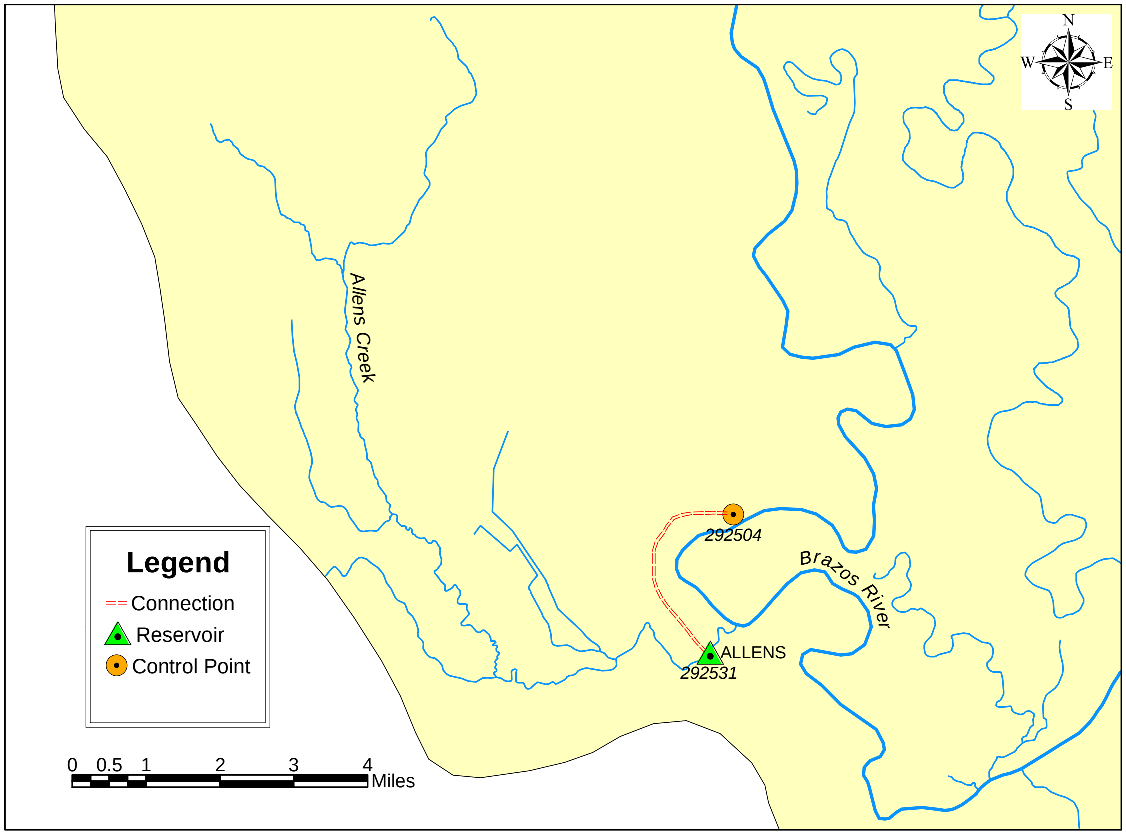


FIGURE 5.20 Location of Allens Creek reservoir and control point in the Brazos River.

A correlation analysis for 1 month into the future was performed for this reservoir, in which storage was correlated with flows in 292504, or 292531 or both. Correlation was analyzed considering all months in the simulation (monthly loop) or using an annual loop beginning in different months. Tables 5.19 and 5.20 show spearman and linear correlation coefficients obtained for this case.

TABLE 5.19 Spearman Coefficients for Storage at Allens Creek and Flows at the Specified Control Point, for 1 month

CP	All months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
292531	**0.3023**	0.2917	0.2895	**0.2469**	0.4003	0.4484	0.4412	**0.4484**	**0.2637**	**0.4191**	**0.4819**	0.4386	**0.4546**
292504	0.2981	0.5034	0.3882	0.2247	0.4849	0.4589	**0.478**	0.2528	0.2353	0.2992	0.3677	0.6661	0.4205
Both CPs	0.3017	**0.5067**	**0.3912**	0.2247	**0.4882**	**0.4589**	0.475	0.2565	0.2435	0.3008	0.3636	**0.6688**	0.4236

TABLE 5.20 Linear Correlation Coefficients for Storage at Allens Creek and Flows at the Specified Control Point, for 1 month

CP	All months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
292531	**0.2407**	0.2448	0.1645	**0.1121**	0.2577	0.3008	0.2789	**0.3143**	0.165	**0.3268**	**0.3632**	0.1965	**0.2947**
292504	0.2038	0.2509	**0.2415**	-0.0988	0.322	0.3171	0.2783	0.0705	0.0193	0.1635	0.2524	0.2974	0.2701
Both CPs	0.2052	**0.2519**	0.2414	-0.0978	**0.3223**	**0.318**	**0.2808**	0.0762	**0.0208**	0.1655	0.2546	**0.2977**	0.271

When defining the reservoirs that should be used to develop the SFF, it is necessary to perform a correlation analysis, in a similar manner as it was developed for the CFDC approach. That is:

- Comparing correlations between naturalized flows at the control point(s) of interest and storage at each individual reservoir, for the same period of analysis of the conditional reliability study.
- After selecting the individual reservoirs with higher correlations, different combinations of these reservoirs are evaluated, selecting the one with the highest correlation.
- It is recommended to perform the analysis with more than one reservoir combination, in order to be able to compare results.

Annual or monthly cycle options

There are two cycling options, annual and monthly; Annual cycle results in one sequence per year, while the monthly cycle results in up to 12 sequences per year. The annual cycle considers seasonality since all the simulations reflect the same season of the year. On the other hand, a monthly cycle considers all the different seasons of the year, so if flows in a region vary greatly with seasons, the exceedance probabilities obtained for the SFF may not be correct. In this case it is recommended to develop a different set of probabilities for each season, using an annual cycle.

Months used to sum flows

The number of months used to sum flows range from 1 to the number of months used in the CRM simulation. If a CRM simulation has not been performed, it is possible to create a SFF for up to 12 months. In any case, although the upper limit in the number of months to be used to sum flows is either 12 or the number of months used in the CRM simulation, if the correlation obtained between storage and naturalized flows is low, it is recommended to use a smaller number of months and constrain the period of analysis.

Probability distribution

Two probability distributions may be applied to the SFF, Weibull and Lognormal a detailed description of these distributions may be found in (*35,36*). Weibull distribution assigns exceedance probabilities based solely on the rank for each ratio; higher values of ratio have lower exceedance probabilities while lower values have higher exceedance probabilities. Lognormal Distribution assigns exceedance probabilities based on the mean and standard deviation of the ratios; it applies the normal distribution to the logarithms of the random variable, the normal probability density function is a bell shaped and symmetrical about the mean. Many hydrologic variables show a marked skewness, since physically they cannot be negative, this probability distribution assigns a zero probability to any negative value.

Regression options for Storage-Flow function

There are 4 different types of regression and an option to adopt user specified coefficients. The four regressions are explained next:

- Exponential regression: This regression was found to give the better results when relating storage and flow. It will predict a non zero flow value for zero storage and will not generate negative flows. The general form of this regression is shown in (5.1).

$$Q = A \cdot \exp^{S/B} \tag{5.1}$$

- Combined regression: This regression may fit when analyzing a portion of the storage-flow values, it can predict negative flows, but there is an option to force the intercept to zero. The general form of this regression is shown in (5.2).

$$Q = A + B \cdot S^{C} \tag{5.2}$$

- Linear regression: It has the same applications and options as the combined regression, but only represents a linear behavior. The general form of this regression is shown in (5.3).

$$Q = A + B \cdot S \tag{5.3}$$

- Power regression: This regression will always predict a zero flow for a zero storage, it is recommended to use it when not considering all the storage-flow values. The general form is shown in (5.4)

$$Q = B \cdot S^{C} \tag{5.4}$$

All four regressions were included in the program, following procedures from (*37*).

Use of intervals of storage volume

Depending on the storage condition being evaluated and the long term simulation results, it may be more convenient to use only a portion of the storage-cumulated flow values when developing the SFF. If an analysis is being done for an initial storage level of 25%, it is possible to have a better fit if only values between 0 and 75% of storage capacity are considered. As mentioned before, a linear or a combined regression may be more suitable for these conditions, while an exponential regression may behave better when considering all values.

Development of the Probability Array

Assigning probabilities to each sequence of flows depends directly from the SFF array being used. It is recommended to use a SFF that was developed for the same combination of control points and reservoirs as well as number of months being used to sum flows. If a SFF array developed for different conditions is used, then results from the model may be erroneous, and reliability results may loose sense.

Computation of diversion and storage reliabilities

Computation of reliabilities is done by using a 2REL record, for water supply diversions or hydroelectric targets, and a new 2SRL record for storage reliabilities. A 2REL table will provide a period reliability, volume reliability and probabilities of equaling or exceeding fractions of the target, considering both months and sequences. Period reliability is calculated based on counting the number of months, not sequences, where the diversion had no shortage. A 2SRL record will provide exceedance probabilities for different fractions of the storage capacity.

5.2.3 Application example

This methodology was applied to the same system and scenarios that were evaluated using the CFDC methodology. The reservoir evaluated is Lake Waco, located in the Brazos River Basin. An analysis will be performed for 1, 3 and 6 months into the future, with all simulations starting in January. As for the CFDC methodology, the objective is to evaluate diversion and storage reliabilities for eight different initial storage levels.

A correlation analysis was performed between flows occurring during the next 1, 3 and 6 months (starting in January) at the control point located in Lake Waco and reservoir storage at different reservoirs in the Brazos River basin. Tables 5.21 and 5.22 show results for Spearman’s and linear correlation coefficients. As done for the CFDC methodology, the four highest coefficients for each period of analysis are highlighted, and the reservoirs with the highest number of highlighted coefficients were selected. Lake Waco has the best correlation, followed by Belton and Proctor. Stillhouse Hollow and Granbury reservoirs were selected as well. Different reservoir combinations were built with these five reservoirs, and are shown in Table 5.23.

A new correlation analysis was performed for each combination; results are shown in tables 5.24 and 5.25. From this analysis, three different reservoir combinations are selected, E, F and H, with F having the highest correlation values.

TABLE 5.21 Spearman's Correlation Coefficients Between Reservoir Storage and Flows at 509431 for 1, 3 and 6 Months

	RESERVOIR											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1 month	0.3201	0.4431	0.4116	0.3541	**0.4511**	**0.5617**	**0.4853**	**0.4325**	0.3816	0.3907	0.3333	0.3662
3 months	0.2854	0.3476	0.3255	0.3105	**0.3486**	**0.4476**	**0.4095**	**0.3661**	0.3206	0.3037	0.2094	0.2183
6 months	0.2076	0.1983	0.2178	0.1738	0.2035	**0.2746**	**0.2760**	**0.2365**	**0.2364**	0.1999	0.1038	0.0880

TABLE 5.22 Linear Correlation Coefficients Between Reservoir Storage and Flows at 509431 for 1, 3 and 6 Months

	RESERVOIR											
	POSDOM	PRCTOR	GRNBRY	WHITNY	AQUILA	LKWACO	BELTON	STLHSE	GRGTWN	GRNGER	SMRVLE	LMSTNE
1 month	0.2600	**0.3638**	0.2881	0.2650	0.3065	**0.3522**	**0.3358**	0.2999	**0.3162**	0.2802	0.1872	0.1444
3 months	0.1610	**0.3318**	**0.2727**	**0.2630**	0.2023	**0.2685**	0.2602	0.2329	0.2445	0.1829	0.0659	0.0439
6 months	0.0700	**0.2564**	0.1903	0.1546	0.0843	**0.1631**	**0.1967**	0.1590	**0.1667**	0.1066	-0.0078	-0.0741

TABLE 5.23 Reservoir Combinations

Combination	Reservoirs		
A	LKWACO		
B	LKWACO	PRCTOR	
C	LKWACO	BELTON	
D	LKWACO	STLHSE	
E	LKWACO	GRNBRY	
F	LKWACO	PRCTOR	BELTON
G	LKWACO	PRCTOR	STLHSE
H	LKWACO	PRCTOR	GRNBRY
I	LKWACO	BELTON	STLHSE
J	LKWACO	BELTON	GRNBRY
K	LKWACO	STLHSE	GRNBRY

TABLE 5.24 Spearman Correlation Coefficients Between Storage in Selected Reservoirs and Streamflows at Lake Waco

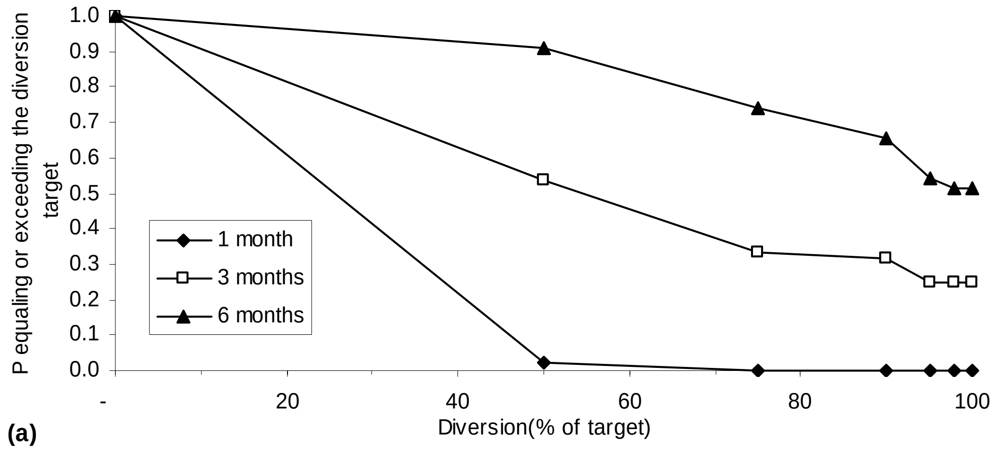
Period	RESERVOIR COMBINATION										
	A	B	C	D	E	F	G	H	I	J	K
1 month	0.5617	**0.5649**	0.5286	0.5098	**0.5719**	**0.5734**	0.5295	**0.5666**	0.5055	0.5473	0.5154
3 months	0.4476	**0.4614**	0.4469	0.4296	**0.4801**	**0.4834**	0.4430	0.4583	0.4367	**0.4756**	0.4366
6 months	0.2746	0.2859	**0.2983**	0.2809	**0.3140**	**0.3323**	0.2892	0.2887	0.2912	**0.3254**	0.2956

TABLE 5.25 Linear Correlation Coefficients Between Storage in Selected Reservoirs and Streamflows at Lake Waco

Period	RESERVOIR COMBINATION										
	A	B	C	D	E	F	G	H	I	J	K
1 month	0.3522	**0.3828**	0.3495	0.3306	**0.3561**	**0.3624**	0.3503	**0.3753**	0.3380	0.3558	0.3397
3 months	0.2685	**0.3076**	0.2696	0.2548	**0.2962**	**0.2843**	0.2765	**0.3180**	0.2612	0.2833	0.2734
6 months	0.1631	**0.2028**	0.1931	0.1665	0.1914	**0.2054**	0.1857	**0.2138**	0.1845	**0.2020**	0.1814

A conditional reliability analysis was performed for each selected reservoir combination. A total of 24 simulations per combination were performed, one for each period and initial storage level, i.e. 1 month 0%, 3 months 0%, 6 months 0%, 1 month 10% and so on.

Storage-Flow frequency curves were developed for each period of analysis using Weibull distribution and an exponential regression. After developing the Probability Array for each simulation, it was possible to calculate reliabilities for diversions and storage at Lake Waco. Figure 5.21 show diversion reliabilities over the next 1,3 and 6 months, starting in January for initial conditions of zero and 10% storage. For a zero initial storage, reliabilities increase with time; but for an initial storage of 10%, reliabilities are 100% for 1 and 3 months, excluding 6 months, when reliabilities for a fraction greater than 95% of the target, are below 100%. Reliabilities for a higher initial storage are always 100%.



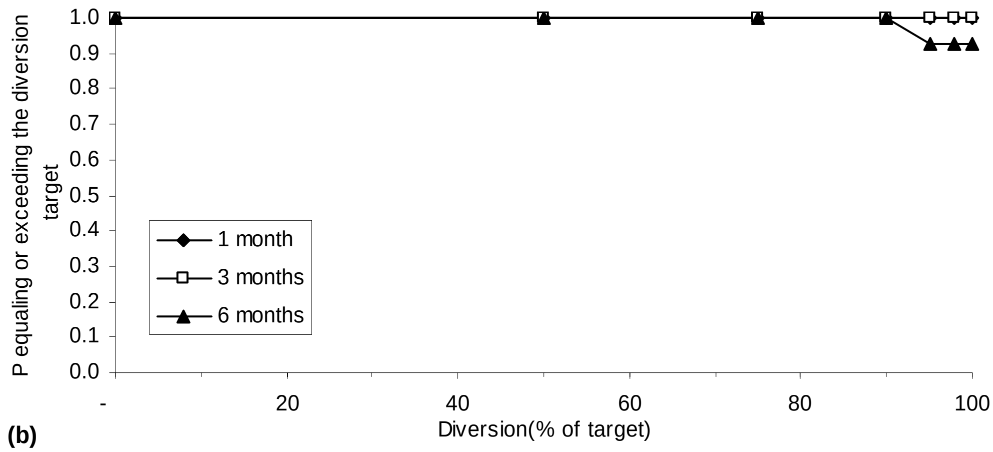


FIGURE 5.21 Diversion reliabilities for 1, 3 and 6 months with initial storages of (a) 0% and (b) 10%, for combination H.

Figure 5.22 shows storage reliabilities for the same periods, but for initial storages of 0%; 50% and 98%. In general, reliabilities increase with initial storage in the reservoir, but when comparing against time, for a high initial storage level, reliabilities for 3 months are higher than those for 6 months. The chart shows that for an initial storage level of 50%, for all periods there is a 100% probability of having the reservoir at least 25% full at the end of the simulation, but in reality, the storage level that has a 100% probability of occurring increases with time in case of not having a high initial storage; for instance, the probability of having the reservoir 50% full is 39% at 1 month, 66% at 3 months and 79% at 6 months.

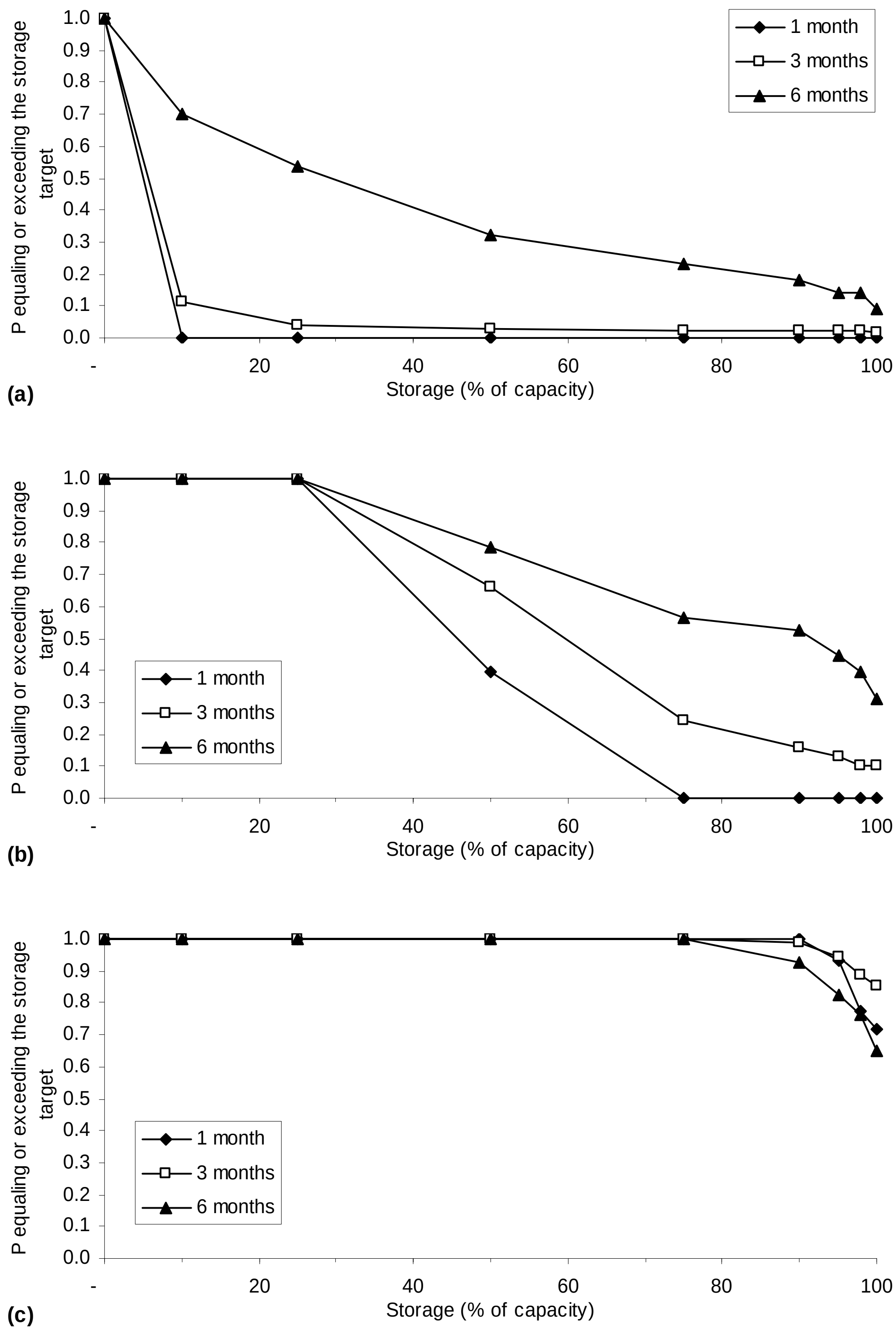


FIGURE 5.22 Storage reliabilities for 1, 3 and 6 months with initial storages of (a) 0%, (b) 50% and (c) 98%, for combination H.

Detailed reliability results are shown in Tables 5.26 and 5.27 for a SFF developed for Lake Waco, Proctor and Belton reservoirs. For all periods, storage reliability increases with initial storage, when comparing reliabilities between periods, reliabilities 3 months ahead are higher than those for 1 month, but when comparing 3 and 6 months ahead, for initial storages greater than 75% reliabilities for 6 months lower than those for 3 months.

TABLE 5.26 Storage Reliabilities for Lake Waco for Different Initial Storage Conditions, for Combination F

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	2.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14724.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	1
	25%	44474.9	0.00	0.00	0.00	0.00	0.00	0.00	0.09	1	1
	50%	96407.8	0.00	0.00	0.00	0.00	0.00	0.39	1	1	1
	75%	154373.6	0.10	0.10	0.12	0.20	0.52	1	1	1	1
	85%	175667.6	0.33	0.33	0.43	0.52	1	1	1	1	1
	90%	183114.5	0.49	0.53	0.56	0.71	1	1	1	1	1
	98%	190200.0	0.72	0.77	0.93	1	1	1	1	1	1
3 months	0%	11174.5	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.11	1
	10%	26092.9	0.03	0.03	0.03	0.03	0.03	0.03	0.11	0.41	1
	25%	60887.7	0.03	0.03	0.03	0.03	0.04	0.11	0.53	1	1
	50%	121738.2	0.10	0.10	0.13	0.16	0.24	0.66	1	1	1
	75%	171065.5	0.47	0.50	0.55	0.59	0.76	1	1	1	1
	85%	182067.7	0.63	0.64	0.67	0.74	1	1	1	1	1
	90%	186027.1	0.68	0.71	0.77	0.85	1	1	1	1	1
	98%	190493.9	0.85	0.89	0.94	1	1	1	1	1	1
6 months	0%	75397.1	0.09	0.14	0.14	0.18	0.23	0.32	0.53	0.70	1
	10%	88533.7	0.10	0.18	0.22	0.26	0.27	0.47	0.64	0.79	1
	25%	111239.7	0.15	0.25	0.28	0.29	0.34	0.53	0.76	1	1
	50%	147158.2	0.31	0.40	0.44	0.52	0.57	0.79	1	1	1
	75%	172412.3	0.39	0.54	0.63	0.67	0.78	1	1	1	1
	85%	180959.9	0.52	0.62	0.74	0.79	0.92	1	1	1	1
	90%	184381.7	0.64	0.72	0.79	0.84	0.97	1	1	1	1
	98%	187541.9	0.65	0.76	0.82	0.93	1	1	1	1	1

TABLE 5.27 Diversion Reliabilities for Lake Waco for Different Initial Storage Conditions, for Combination F

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table 100	98	95	90	75	50	0
1 month	0%	5137.5	4485.7	0.0	12.7	0.00	0.00	0.00	0.00	0.00	0.02	1
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	6830.7	36.1	55.9	0.25	0.25	0.25	0.32	0.33	0.54	1
	10%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	5047.1	73.1	85.8	0.51	0.51	0.54	0.66	0.74	0.91	1
	10%	35505.2	201.9	97.6	99.4	1	1	1	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1

The same conditional reliability analysis was done for the next two reservoir combinations with the highest correlations between storage and naturalized flows. These are combinations H and E. Detailed reliability results are shown in Tables B.1 to B.6 in Appendix B.

Figure 5.23 compares storage reliabilities for the next 3 months obtained for three different reservoir combinations. It is possible to observe that for an initial storage of 10% and 50%, the combination containing Lake Waco, Proctor and Belton reservoirs (combination F) gives a higher correlation than combinations H and E which still produce similar results between each other. If the initial storage is increased to 98%, then reliabilities for storage levels greater than 75% of the capacity, differences between combinations E and H increase, but combination F stills produces a higher reliability than the other two combinations.

Figure 5.24 shows a comparison for 6 months ahead, practically the same behavior is observed, where combination F gives higher reliabilities for all periods, and combinations E and H produce very similar results. There is one exception, for an initial storage of 50%, the reliability for 100% of storage capacity is higher for combinations E and H than for combination F. Differences between combination F and the others are higher for 1 and 3 months, while for 6 months they are reduced.

It appears that if Granbury reservoir is added to the analysis, it produces a more conservative reliability.

When comparing only reliabilities of meeting 100% of the capacity, Figure 5.25 shows that for 1 month, differences are as high as 10% for an initial storage of 85 and 90%, but are negligible for 98%. Again, combination F predicts a higher reliability. For 3 months, differences are reduced and combinations E and H are still more conservative than F. For 6 months, differences increase again and combination F produces higher reliabilities except for an initial storage of 50% where it falls below combinations E and H, which for initial storages below 75% produce very similar reliabilities but with higher initial storages produce different results.

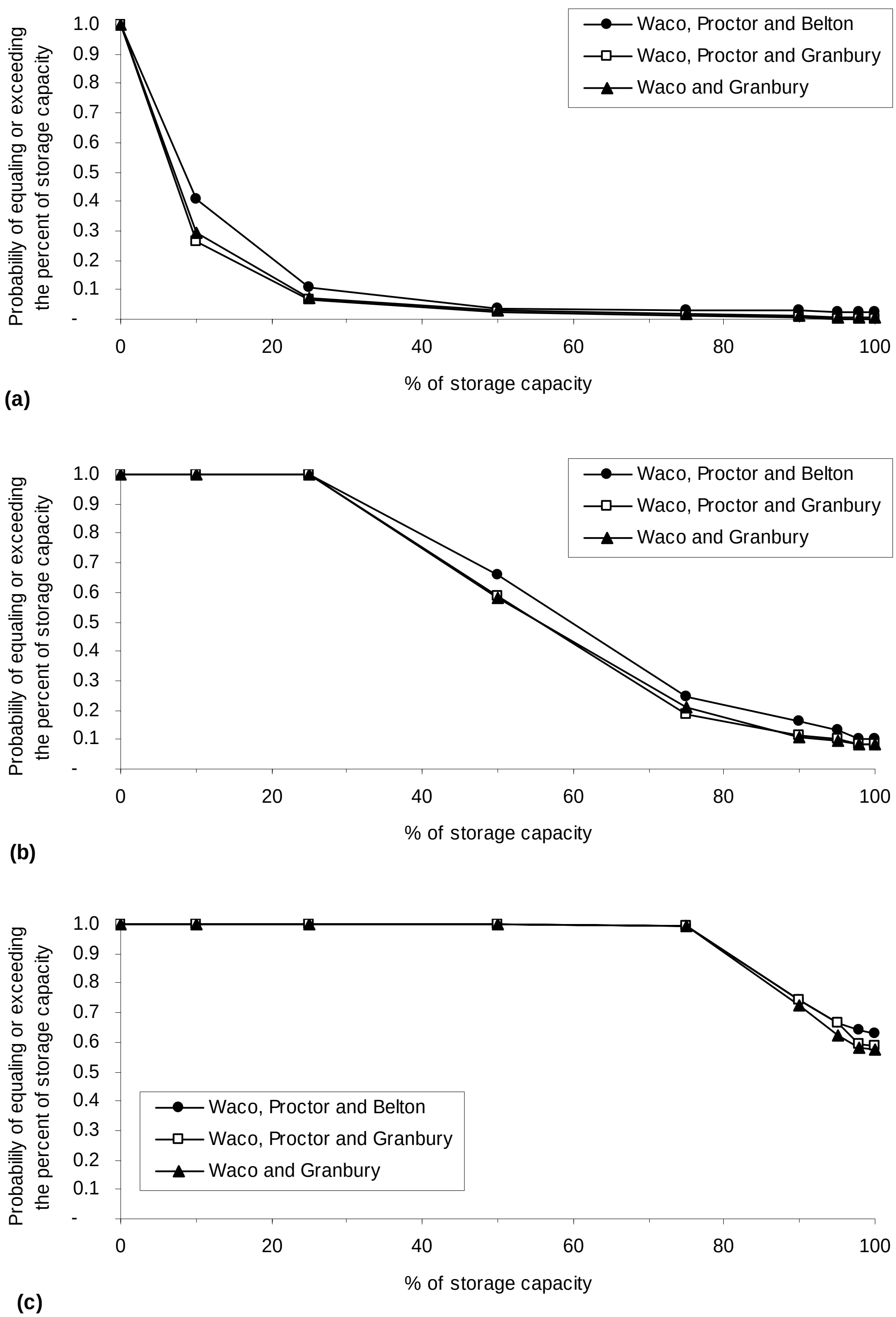


FIGURE 5.23 Comparison of storage reliabilities at Lake Waco, for 3 months ahead, with initial storage at (a) 10%, (b) 50%, (c) 85% and three different reservoir combinations.

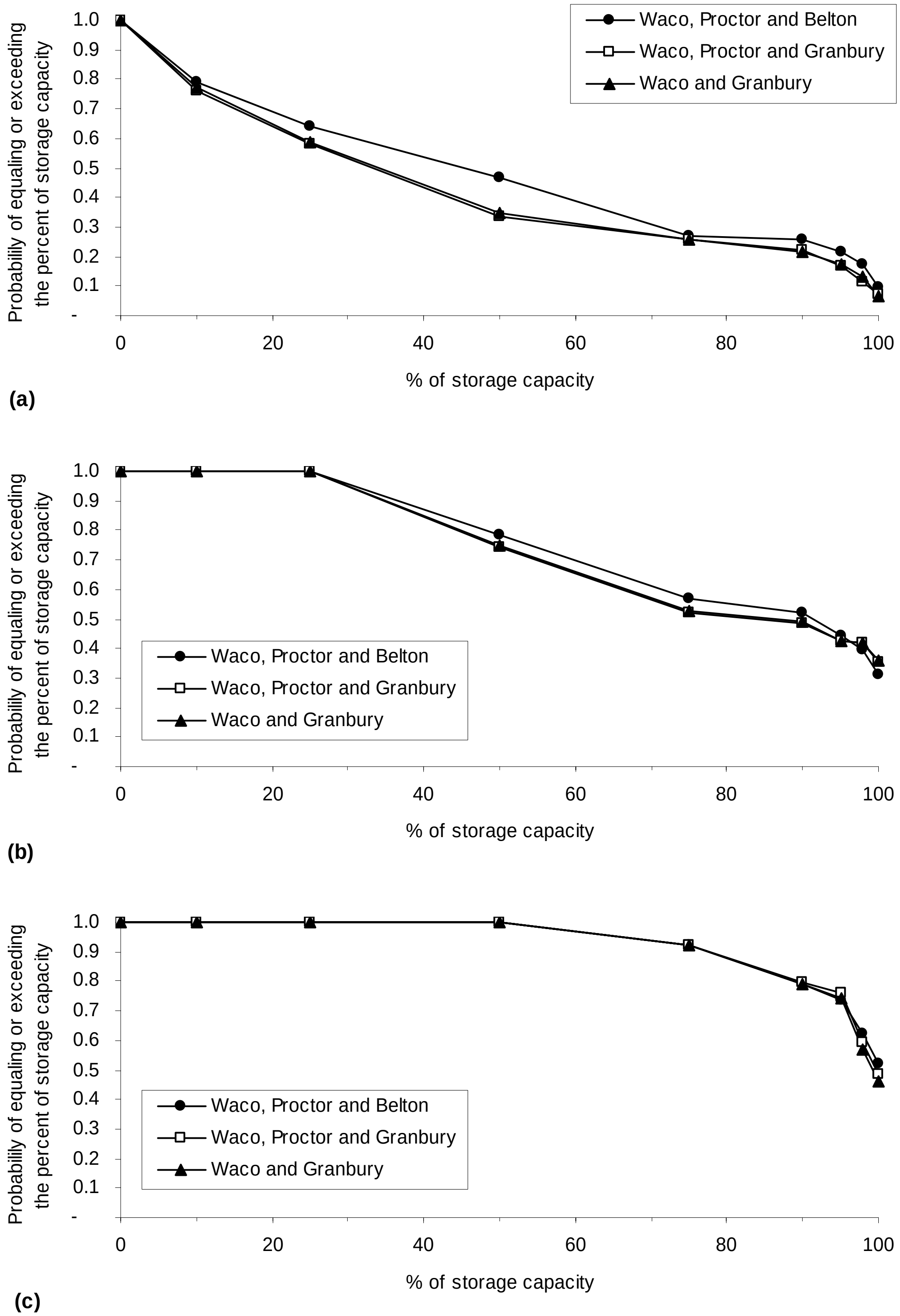
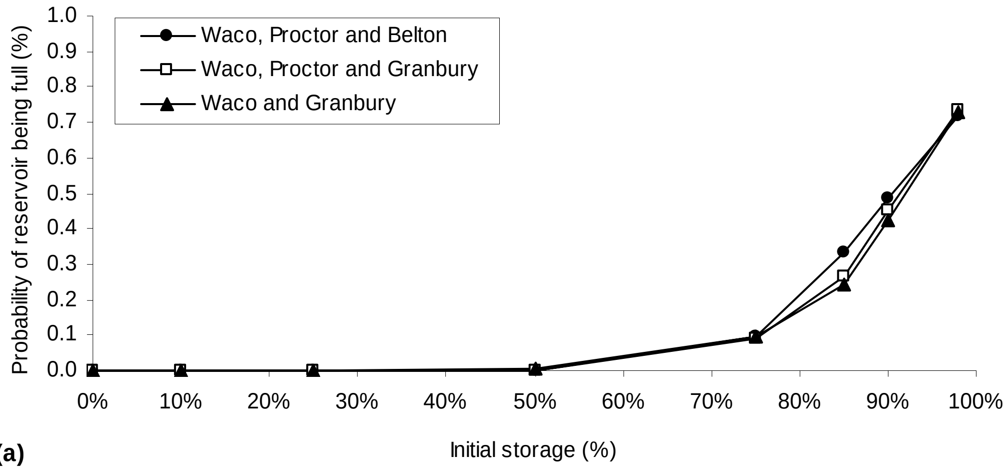
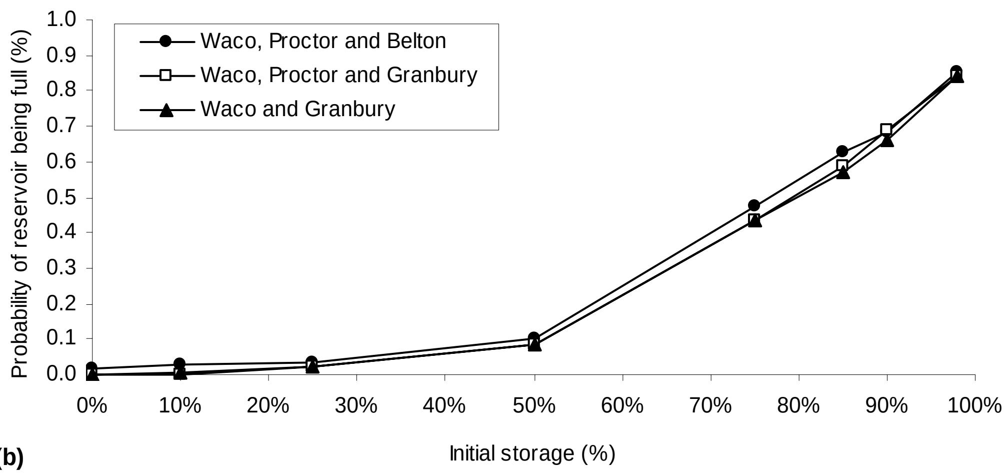


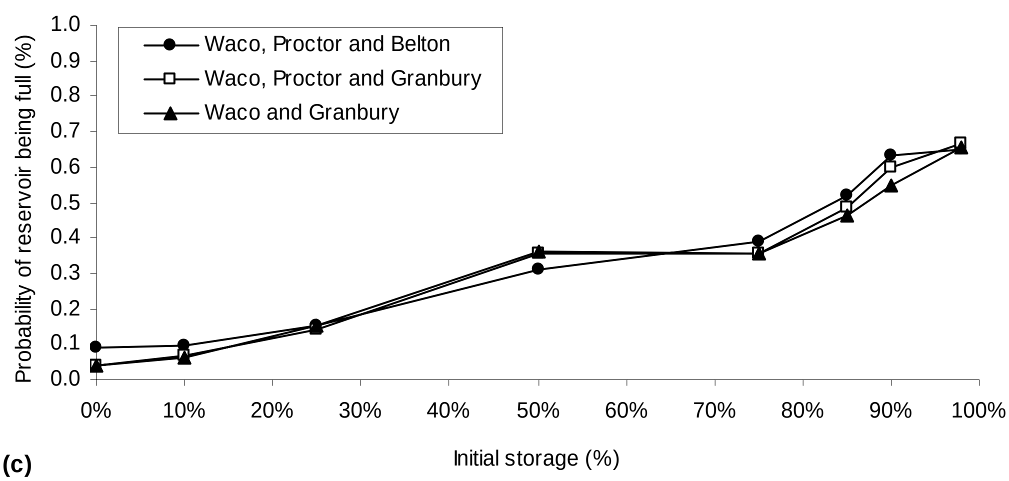
FIGURE 5.24Comparison of storage reliabilities at Lake Waco, for 6 months ahead, with initial storage at (a) 10%, (b) 50%, (c) 85% and three different reservoir combinations.



(a)



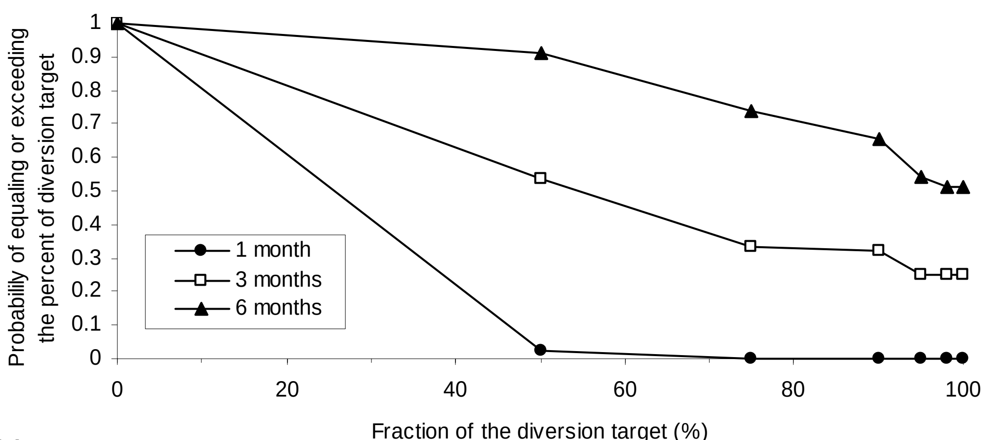
(b)



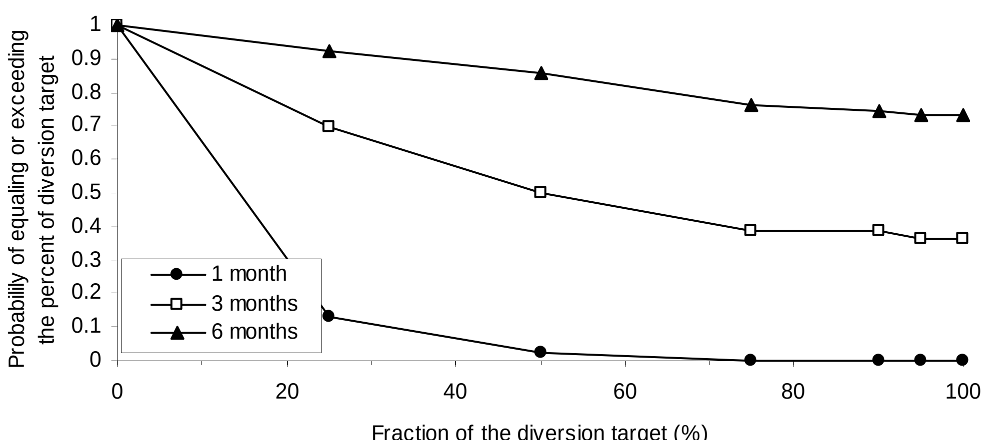
(c)

FIGURE 5.25 Comparison of period reliabilities for storage at Lake Waco with 3 different reservoir combinations, for (a) 1 month, (b) 3 months, (c) 6 months.

There are two ways to calculate diversion reliabilities, (1) by using the number of months or (2) using the number of sequences, where the diversion target was fully met. In order to allow a comparison to be made between the SFF methodology and the CFDC one, the second option was used, since it is the one the CFDC uses. Figure 5.26 shows the different diversion reliabilities that can be obtained when counting sequences or months. It can be observed that reliabilities are higher when counting months, since there are a higher number of months than sequences. Assume there are 58 sequences of 3 months each, for a total of 174 months. If there is a shortage in 1 month, then the reliability would be 173/174*100 or 99.4%, while when considering sequences the reliability is 57/58*100 or 98.3%.



(a)



(b)

FIGURE 5.26 Diversion reliabilities when counting (a) sequences, (b) months.

A final comparison between reservoir combinations was done, this time between the combination with the highest correlation involving reservoir and storage (Waco, Proctor and Belton), and considering only Lake Waco.

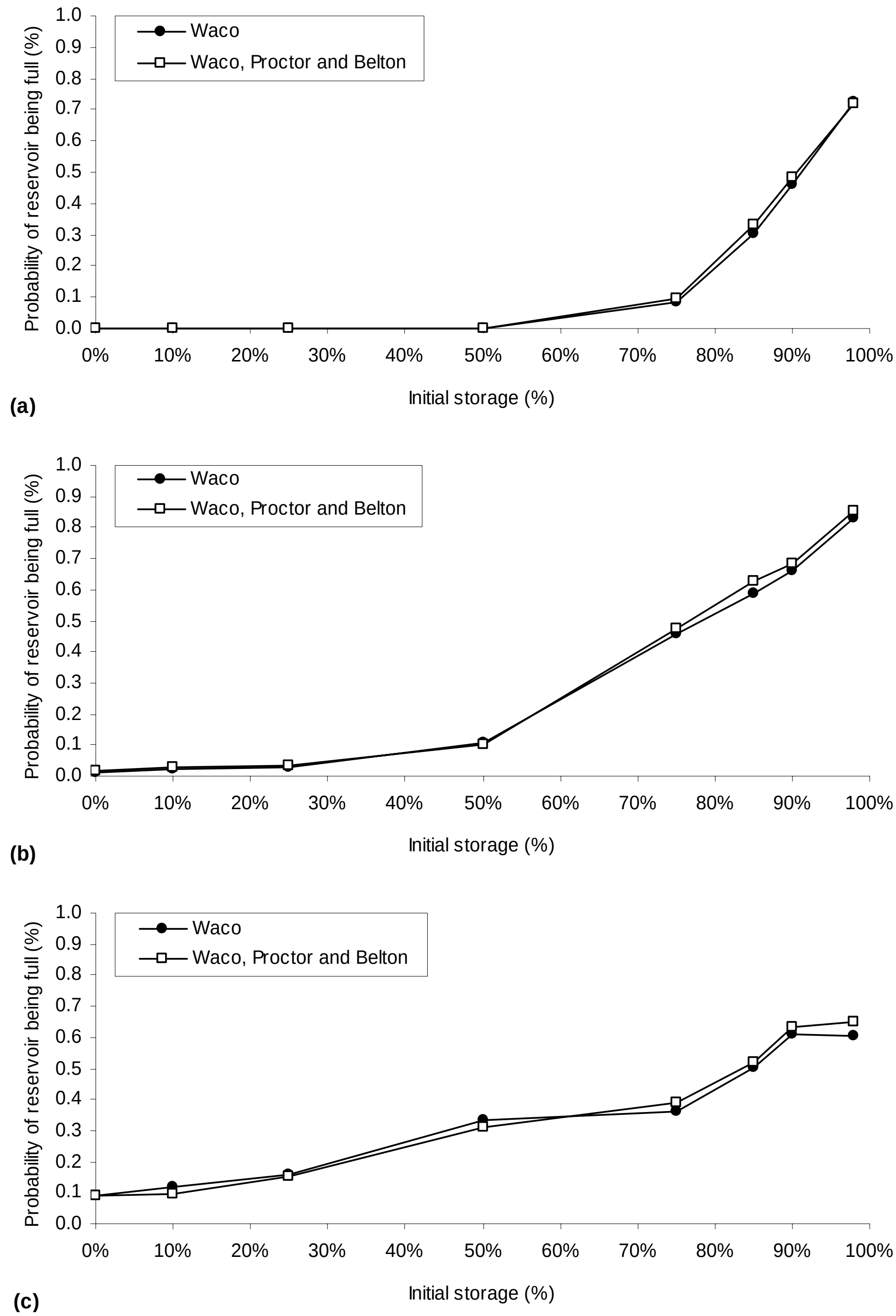


FIGURE 5.27 Comparison of probabilities of Lake Waco being full at the end (a) 1 month, (b) 3 months and (c) 6 months, with combinations F and A.

It is observed that combination A produces results similar to those of F, but still combination F gives higher reliabilities as it occurred with combinations E and H. Combination A gives reliabilities between those obtained from combinations F and E or H.

Storage-Flow Frequency using Lognormal distribution

As mentioned previously, there is an option to apply the lognormal distribution when developing the SFF array. That option was used in this section, and the same analyses done previously were repeated. Tables B.7 to B.14 show storage and diversion reliabilities for combinations F, E, H and A. Reliabilities have behavior similar to that identified when using Weibull distribution, as seen in Figure 5.28 reliabilities increase with initial storage and in the case of a low initial storage, reliability also increases with the period of analysis.

When comparing results obtained for different reservoir combinations, it is observed that for 3 and 6 months storage reliabilities are higher for combination F than for combinations E and H, which exhibit almost identical results, also differences between combinations decrease and reliability curves are smoother than when using Weibull distribution. Figures 5.29 and 5.30 show storage reliabilities for those 3 reservoir combinations.

Figure 5.31 displays a comparison of period reliability of storages for 1, 3 and 6 months, using 3 different combinations. In this case, all three reservoir combinations have the same trend and differences between combinations are smaller than those obtained when using Weibull distribution, in some way minimizing the effect of the reservoir combination. In addition, when using lognormal distribution, the storage reliability curve is smoother than the one obtained using Weibull (Figure 5.25), giving the impression of a more even distribution of reliabilities. This can be validated when comparing Figures 5.32 and 5.27, where Figure 5.27 shows curves with sudden changes in slope, while Figure 5.32 shows soft variations.

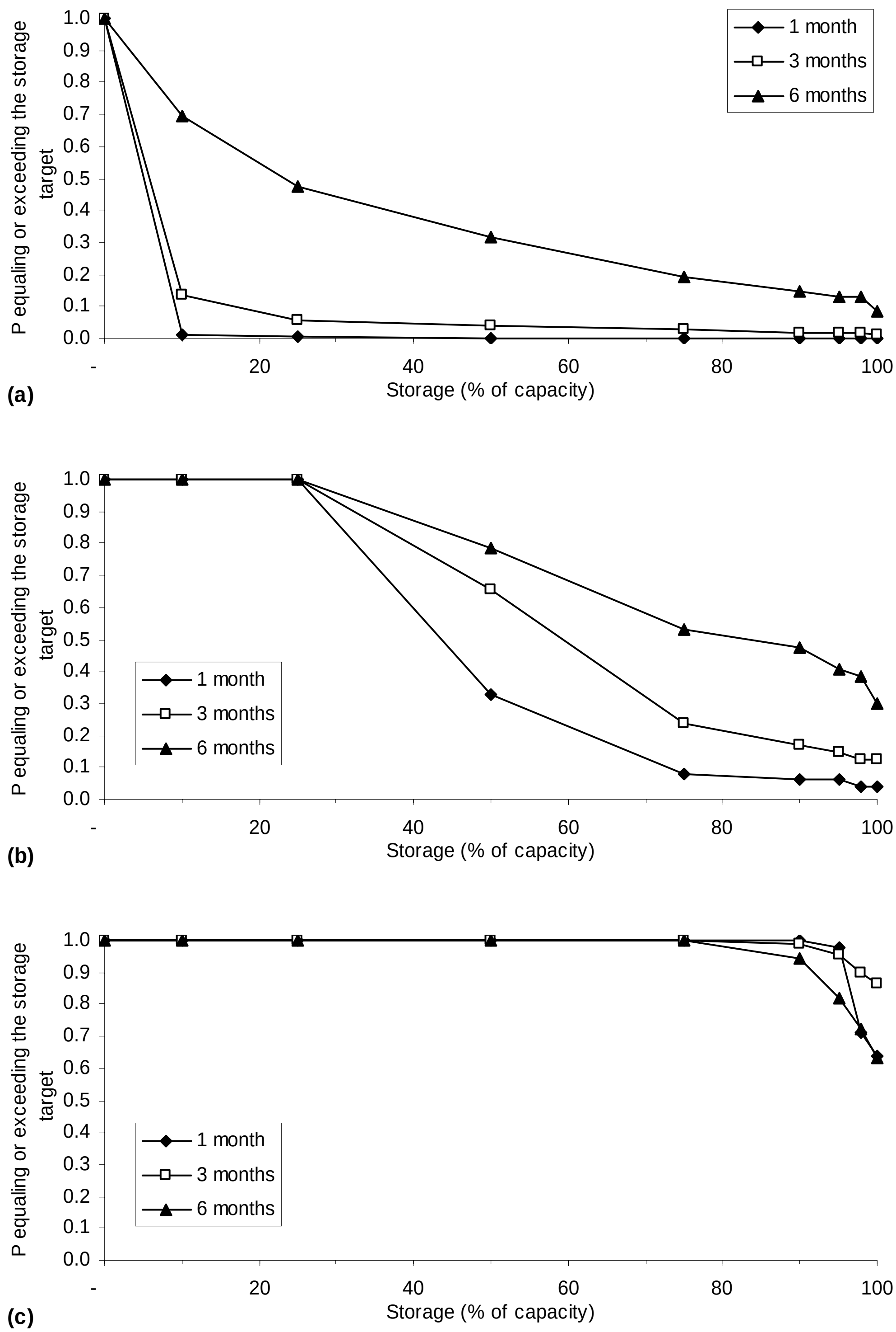


FIGURE 5.28 Storage Reliabilities for Lake Waco with initial storages of (a) 0%, (b) 50% and (c) 98%.

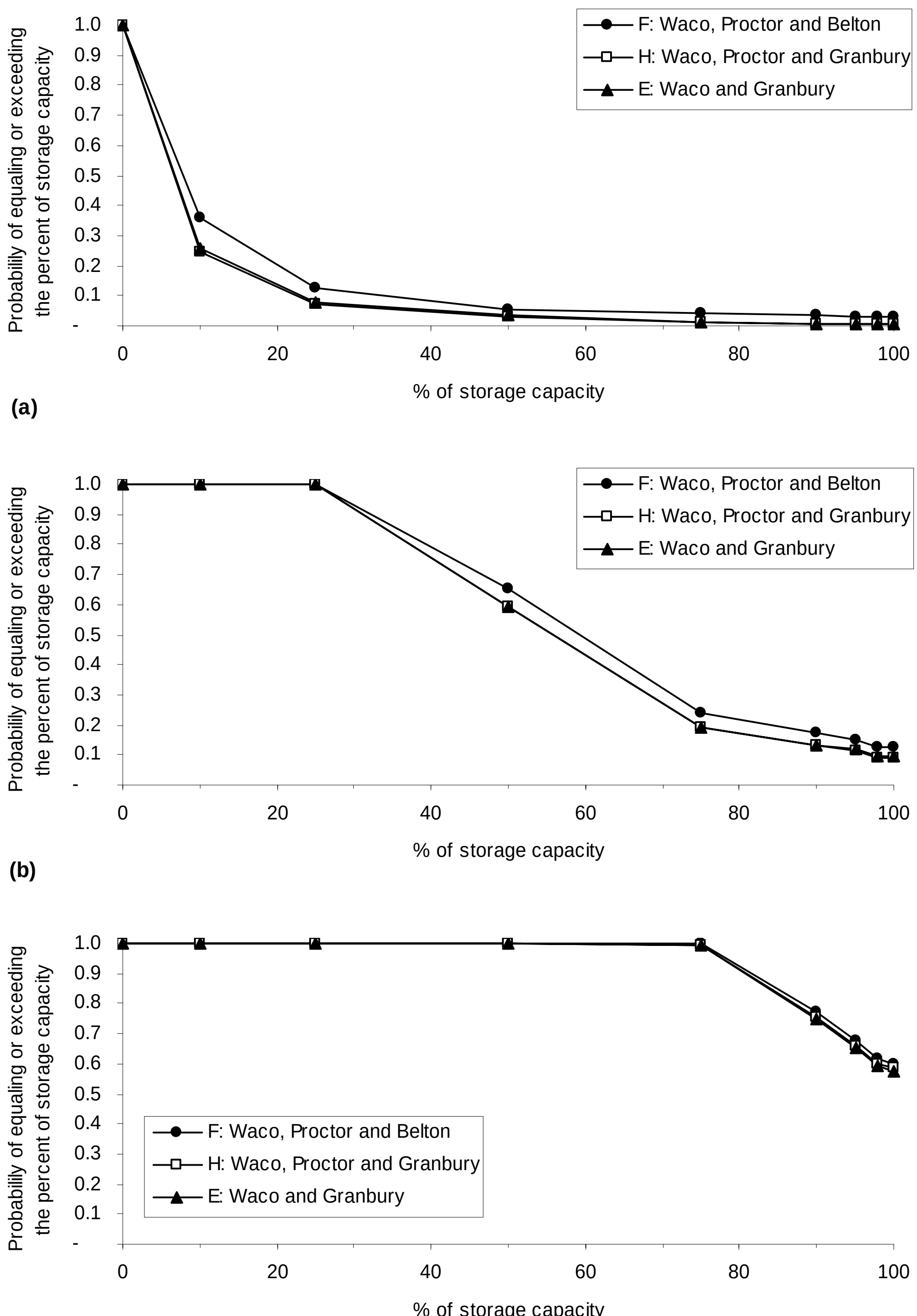


FIGURE 5.29Comparison of storage reliabilities at Lake Waco, for 3 months, using lognormal distribution and initial storages of (a) 10%, (b) 50%, (c) 85%.

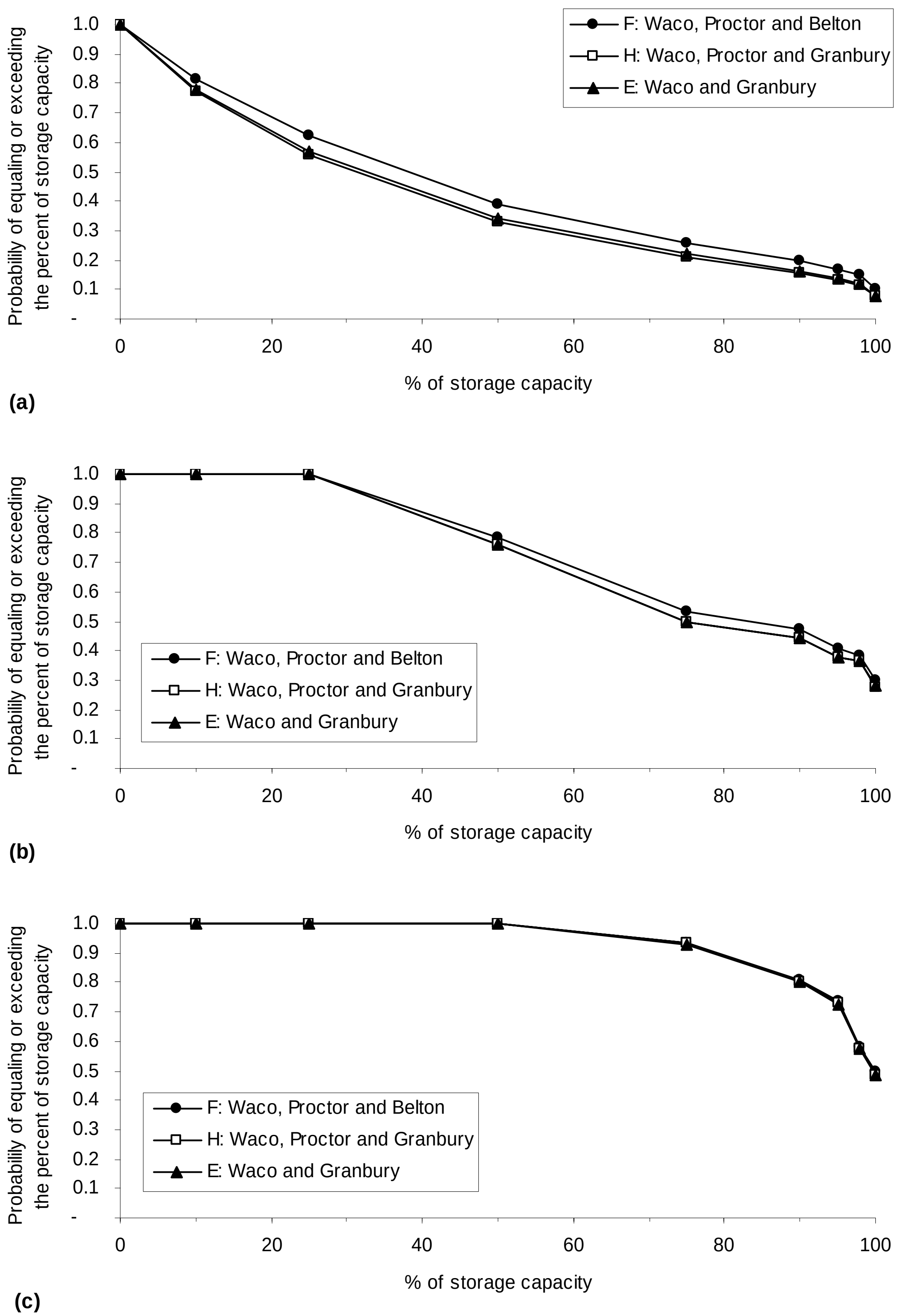


FIGURE 5.30 Comparison of storage reliabilities at Lake Waco, for 6 months, using lognormal distribution and initial storages of (a) 10%, (b) 50%, (c) 85%.

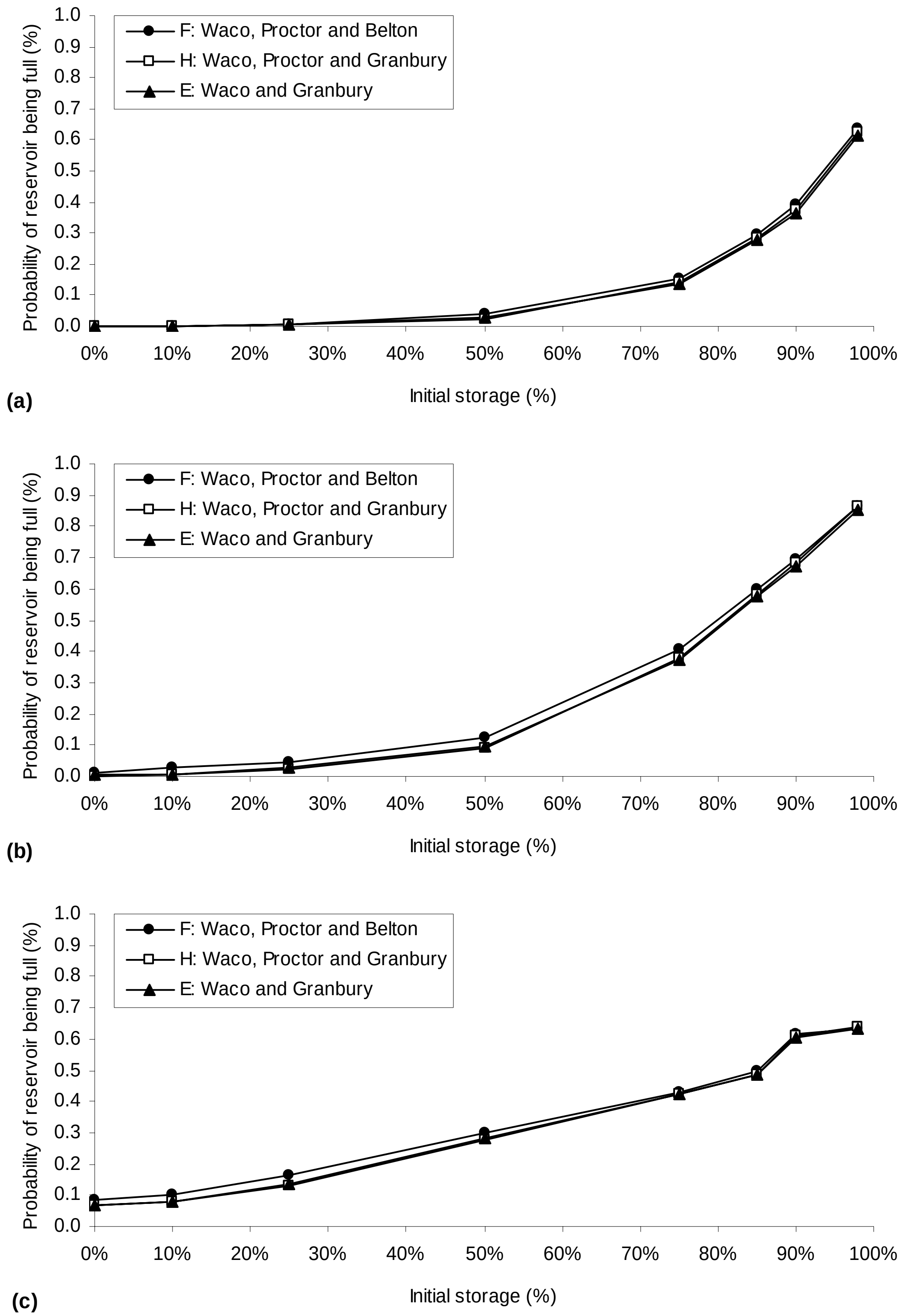


FIGURE 5.31 Comparison of period reliabilities for storage at Lake Waco, using lognormal distribution, for (a) 1 month, (b) 3 months, (c) 6 months.

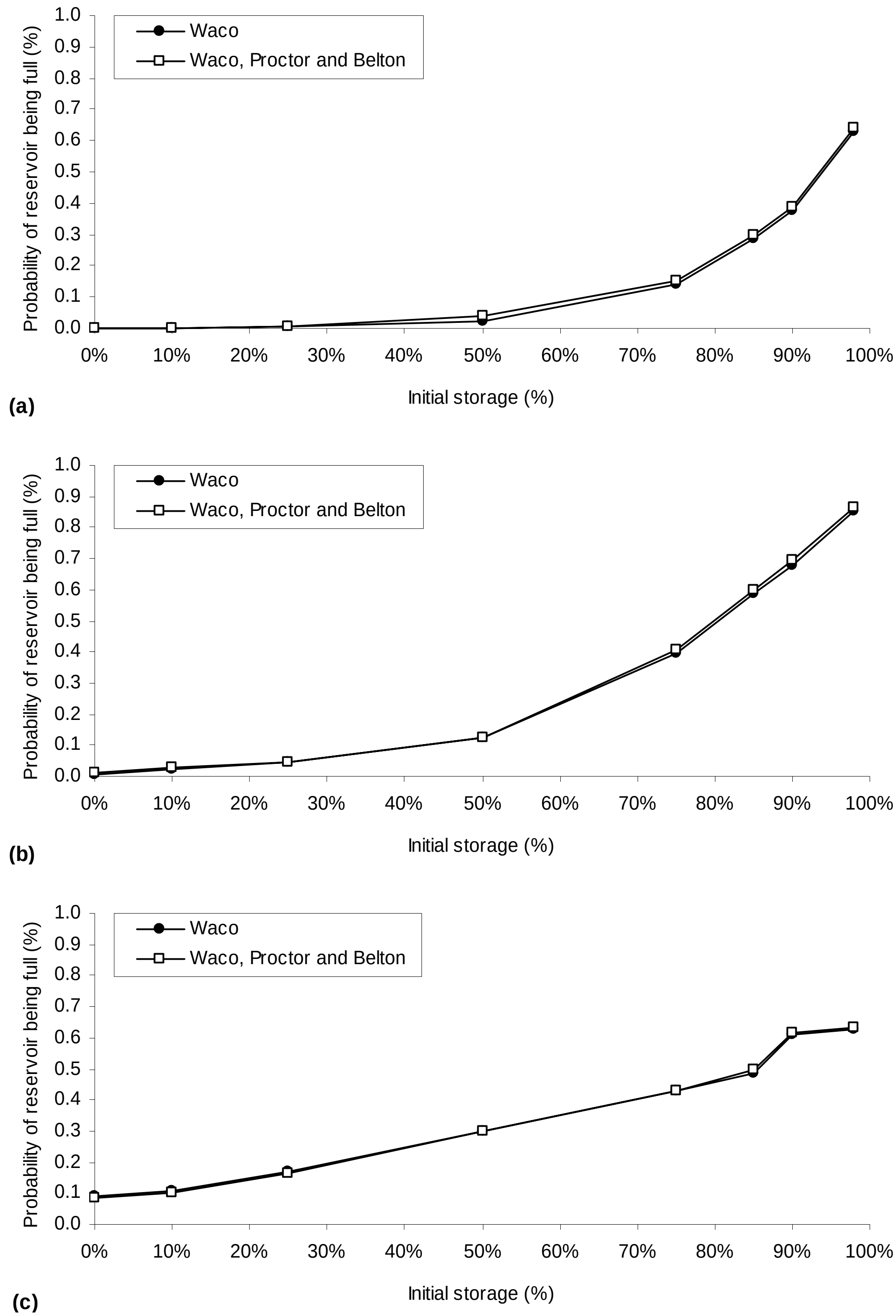


FIGURE 5.32 Comparison of period reliabilities for storage at Lake Waco, using lognormal distribution, for (a) 1 month, (b) 3 months, (c) 6 months.

Figure 5.33 compares storage reliabilities for Lake Waco using Weibull or lognormal distributions. Differences are as high as 10% for one month, and decrease with time, 6% for 3 months and 4% for 6 months. There is not a generalized behavior, but in most cases, when having low initial storage levels, lognormal distribution gives higher reliabilities. For high initial storages, there is no noticeable trend and sometimes Weibull produces higher reliabilities than lognormal or vice versa. It was detected that the behavior of the reliability curve depends greatly on the reservoir combination, but in any case the shape for the lognormal reliability curve is much smoother than the one obtained with Weibull (see Figures B.1-B.3).

Based on the theory involved in both probability distributions, and in the plots created, lognormal distribution may be the distribution that better represents this phenomenon, since it considers the statistical properties of the random variable and the reliability curve shows a smooth increment of reliability with initial reservoir content. It was also showed that by using a lognormal distribution, the impact of the reservoir combination chosen is minimized, obtaining similar reliabilities for different combinations.

However, when applying the Weibull distribution, results are still coherent and to the best of the author’s knowledge, valid.

Comparison between SFF and Equally likely reliabilities

Figure 5.34 shows a comparison between storage reliabilities obtained using SFF-Weibull, SFF-lognormal and the equally likely methodologies. As described earlier, the equally likely approach considers every sequence to have the same probability, regardless of the storage condition. As expected, when considering low initial storage levels, the equally likely option produces higher reliabilities, since the average of flows is greater than the flows expected under these conditions. For an initial storage of 50%, the equally likely option still produces higher reliabilities, but the differences with the SFF reliabilities decrease. For initial storages of 85% and up, SFF reliabilities are higher than those obtained with an equally likely approach; this is due to the fact that under high storage conditions, high flows are more likely than low flows, therefore a higher reliability is expected with a SFF methodology. There is an initial storage value for which both, equally likely and SFF reliabilities are similar, in this case it would be between 50 and 85%.

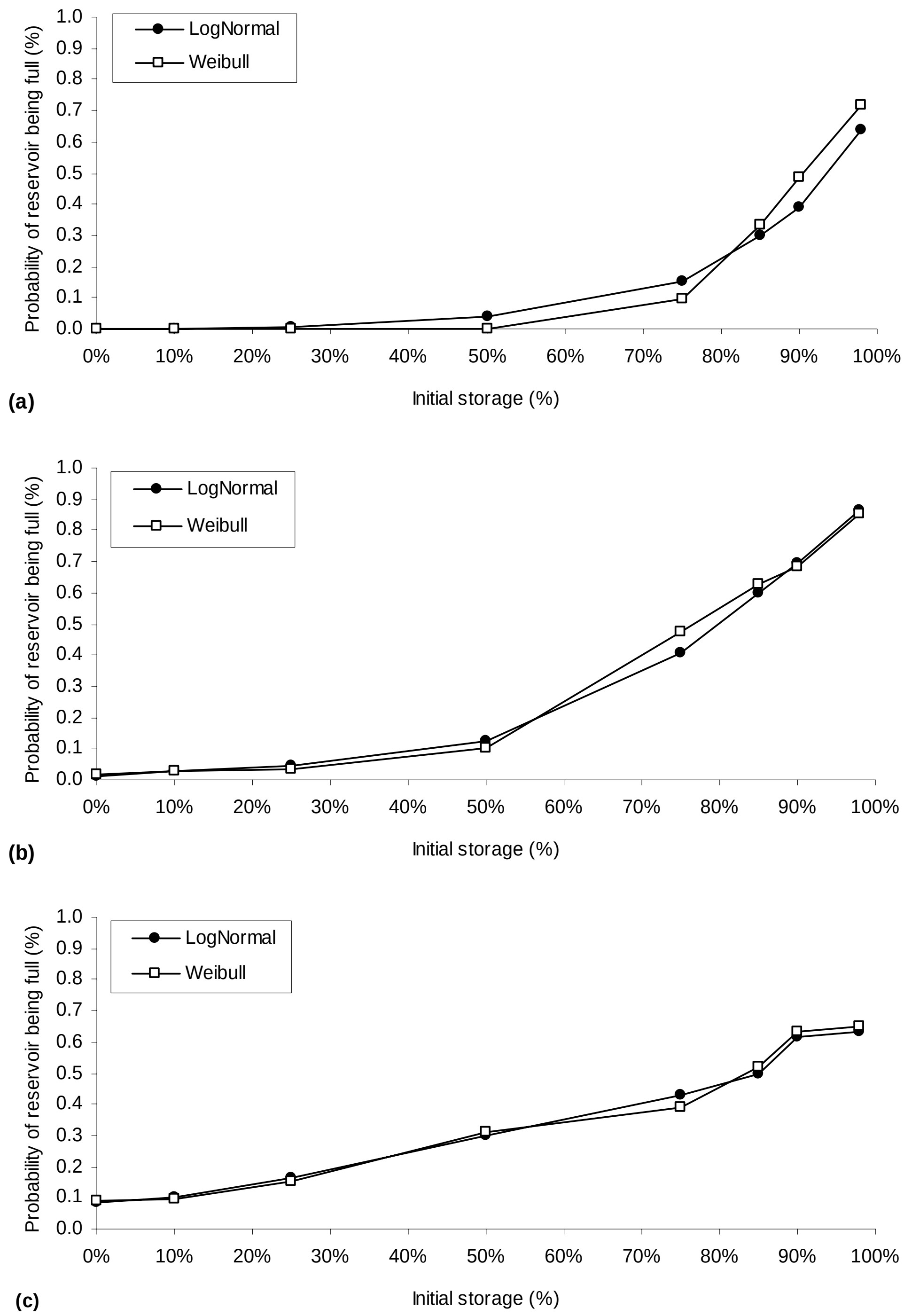


FIGURE 5.33 Comparison of storage reliabilities using Weibull and lognormal distributions, using combination F, for (a) 1 month, (b) 3 months, (c) 6 months.

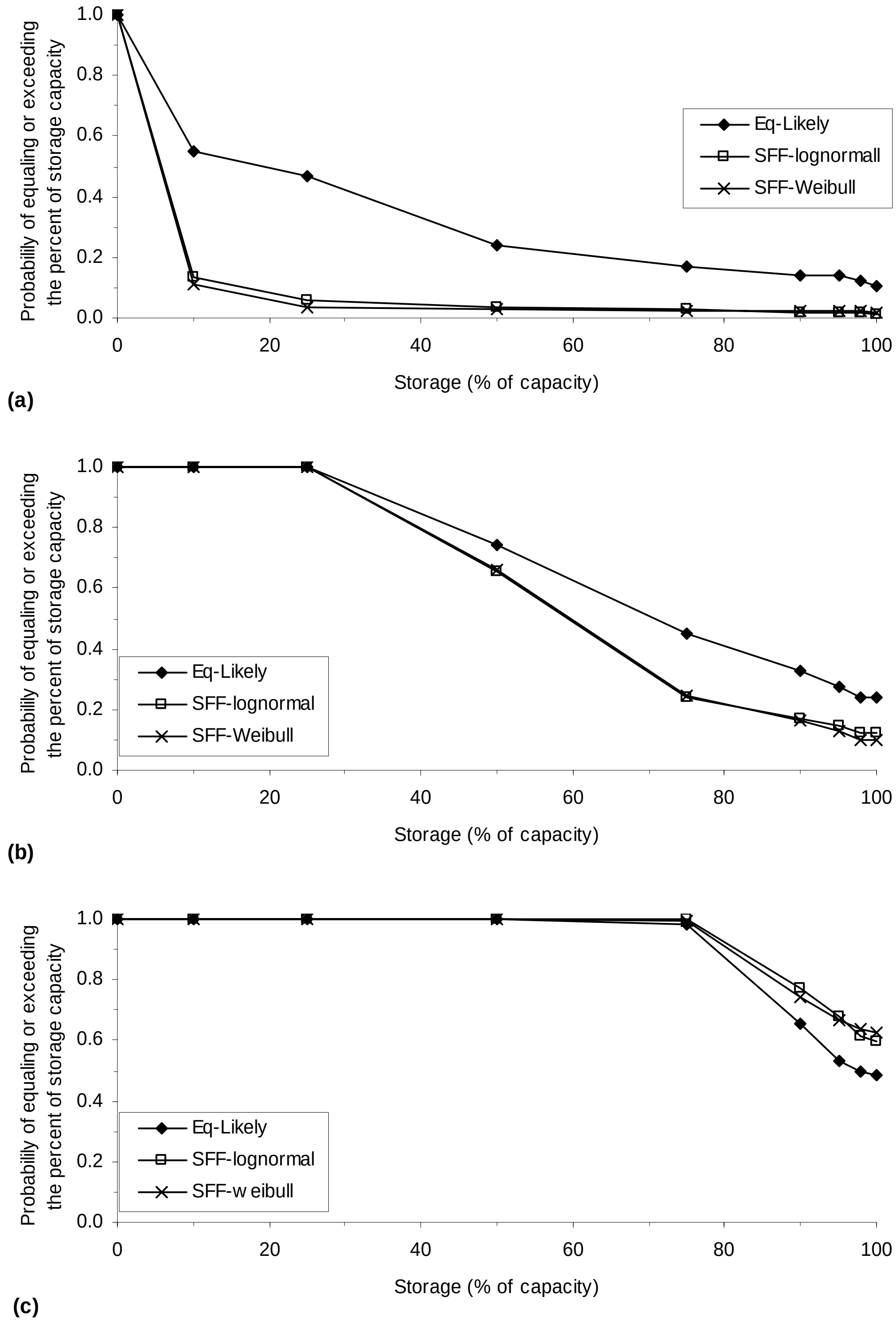


FIGURE 5.34 3 months storage reliabilities for Lake Waco using equally likely, SFF-Weibull and SFF-lognormal approaches, with initial storages of (a) 0%, (b) 50%, (c) 85%.

5.3 COMPARISON BETWEEN CFDC AND SFF MODELS

A comparison between the Storage-Flow frequency and the Conditional Frequency Duration Curve models was done, using storage and diversion reliabilities obtained from the several runs executed in for this study. These comparisons were made mainly for storage reliabilities, since diversion reliabilities were 100% for storage levels greater than 0%, limiting the analysis.

The first comparison was done using those reliabilities obtained from the reservoir combination that offered the highest correlation between storage and flow; for the CFDC model this combination included Lake Waco, Proctor and Granger reservoirs, while for the SFF model it included Lake Waco, Proctor and Belton reservoirs.

As shown in Figure 5.35, it was found that the SFF model is more conservative for low initial storage conditions, while for high storage conditions it produces higher reliabilities than the CFDC model, with the exception of a one month analysis, where the CFDC model had an abrupt jump between 90 and 98% initial storages (Figure 5.35a). These kinds of jumps in reliabilities are produced when switching levels within the CFDC, for instance, from intermediate storage to high storage conditions. These jumps are not found when using the SFF model, since it produces a smooth transition between initial storage levels.

In addition, when the conditional reliability curve from the CFDC model, had a low R^2 value, it was possible to have reliabilities that decreased as the initial storage increased. This was the case for the six months simulation, in which for storages above 85% the simulation results were so scattered that it was not possible to have a good fit between storage and naturalized flows see Figure A.21. This behavior was not identified for the simulations executed with the SFF model. However, there is one situation in which diversion reliabilities can increase while storage decreases; if the diversion target for a water right is dependant on the storage in a reservoir, i.e diversion target decreases as reservoir storage decrease, it is possible to have a higher diversion reliability for a lower storage level.

Comparisons were also done when both models used the same reservoir combination, such as when using Lake Waco and Granbury or when using only Lake

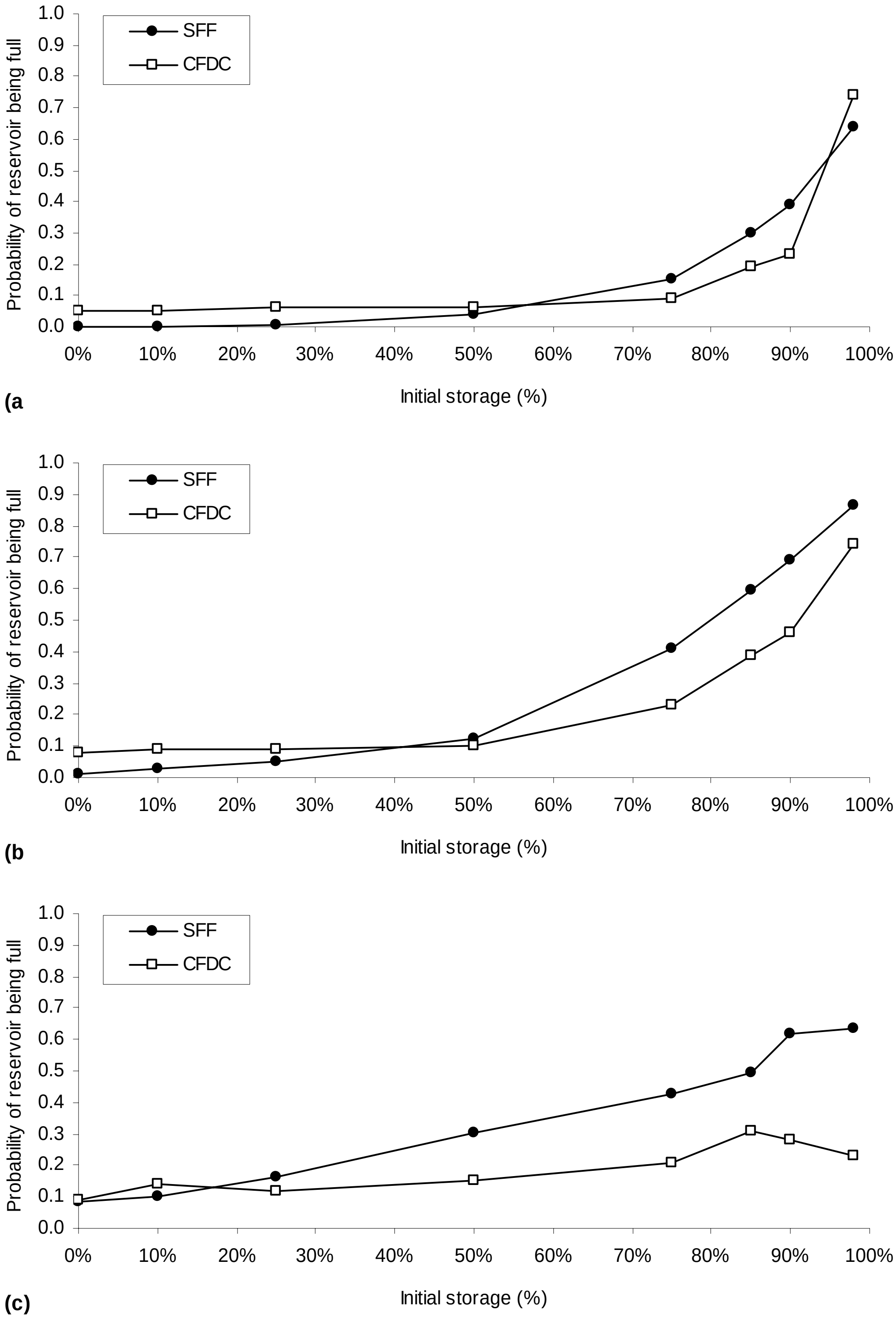


FIGURE 5.35 Storage reliabilities for Lake Waco at (a) 1 month, (b) 3 months, (c) 6 months when using the reservoir combination with the highest correlation in each model.

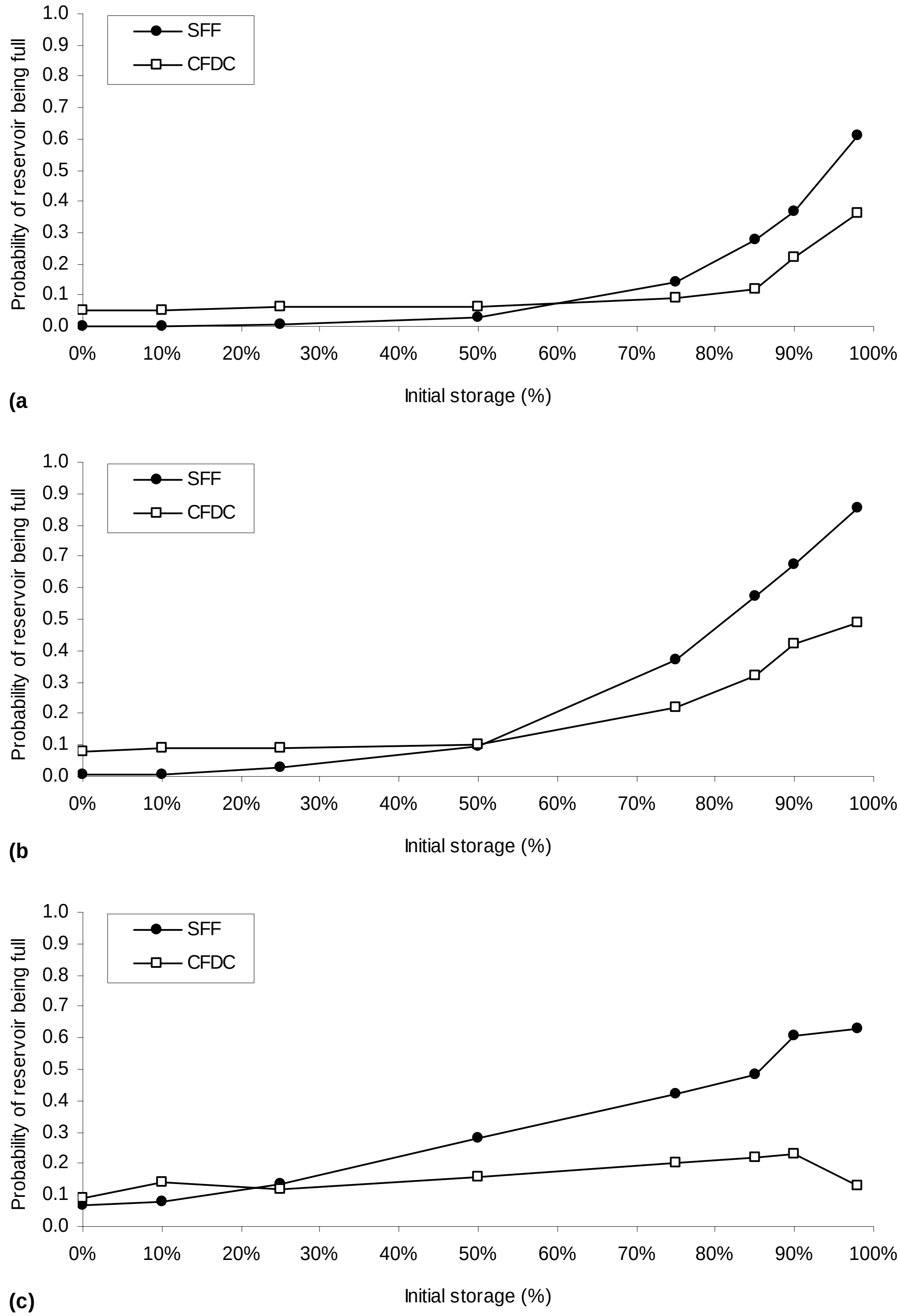
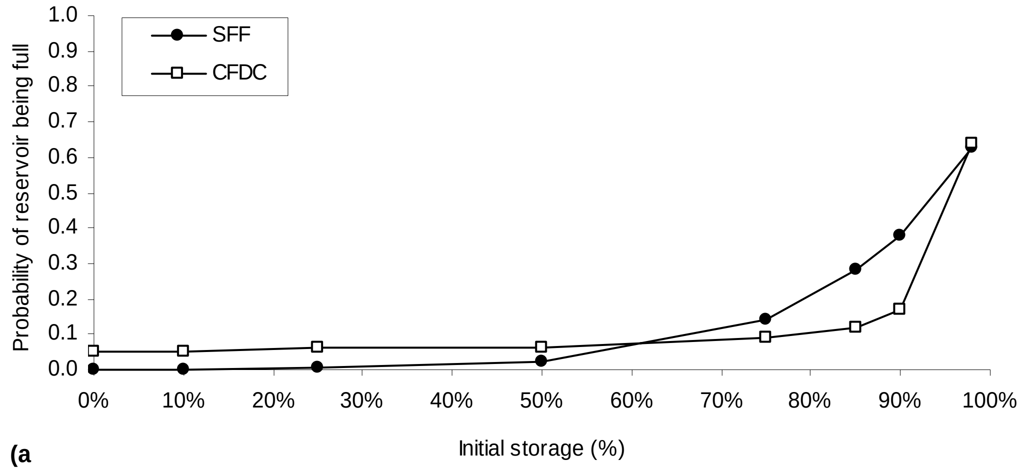
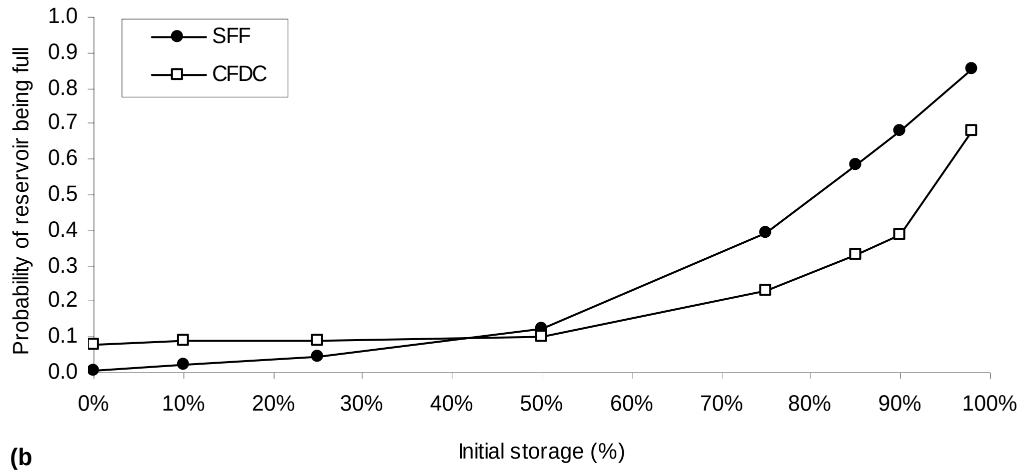


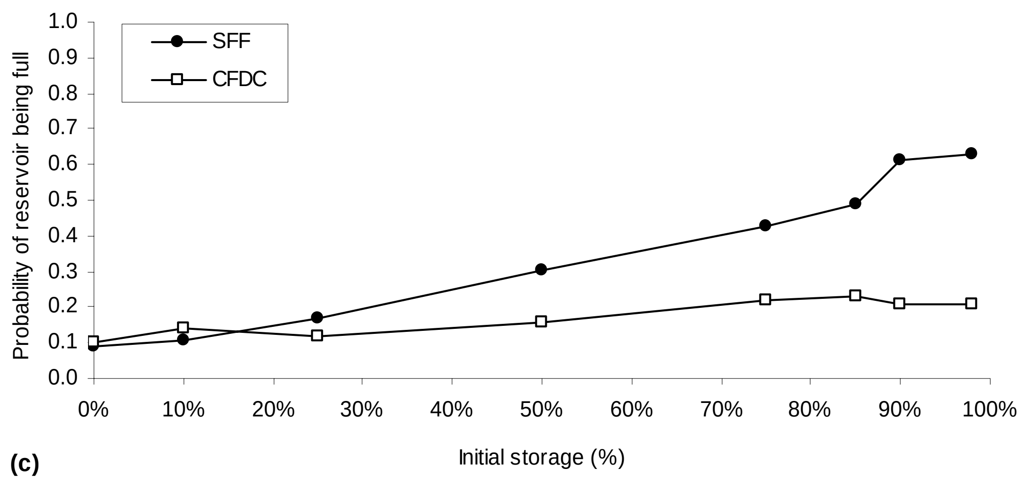
FIGURE 5.36 Storage reliabilities for Lake Waco at (a) 1 month, (b) 3 months, (c) 6 months when using a reservoir combination including Lake Waco and Granbury reservoirs.



(a



(b



(c)

FIGURE 5.37 Storage reliabilities for Lake Waco at (a) 1 month, (b) 3 months, (c) 6 months when using a reservoir combination including Lake Waco reservoir.

Waco. These results are shown in Figures 5.36 and 5.37 respectively. It was found again that for low storage levels, the SFF model is more conservative than the CFDC, and for high storage levels, the SFF model produces higher reliabilities.

Differences in reliabilities between both models are considerable, being as high as 37% (Figure 5.36c) when the conditional reliability curve from the CFDC model had a high R^2 value or as much as 50% (Figure 5.36b) for a low R^2 value.

Another difference found between both models was related to the equally likely results found from each model. While the SFF model defines an initial storage level for all the reservoirs in the system, the CFDC model defines initial storage levels only to those reservoirs (up to 12) defined in the input data. This can result in slightly higher reliabilities for the CFDC model.

CHAPTER VI
GIS DISPLAY OF WRAP RESULTS

6.1 DESCRIPTION

As described in chapter 1, the Water Rights Analysis Package (WRAP) is a very powerful model that allows the simulation of the use of the water resources of a river basin or multiple basins. All the WRAP output is contained in a text file, TABLES reads it and develops a more meaningful output so that the user can visualize the results. But in some cases, it is better if the user could visualize these results in a geographical display.

A simple tool to display WRAP results in ArcGIS 8x or higher was developed (*38,39*). The tool reads WRAP output files and allows the user to visualize with colors the most common variables. It is also possible to visualize time series for another set of variables.

6.2 REQUIREMENTS

- The tool requires ArcGIS 8x or higher
- One shapefile containing the control points included in the simulation. The attribute table this shapefile should have a BWAM_ID field, containing the control point identifier that is used within WRAP.
- A shapefile containing the reservoirs included in the simulation, if no reservoirs are included in the simulation, this shapefile and any other input related with reservoirs is not necessary. The shapefile should have a field named BWAM_ID containing the reservoir identifier used within WRAP.
- A WRAP output file
- A text file with a .BES extension, this file contains reservoirs capacity information and can be easily created by using the recycling option within the JD record in the WRAP input file.

6.3 PROCEDURE TO USE THE TOOL

- The tool is contained in a file named display.dll, this file should be loaded into ArcGIS by right clicking on any toolbar and selecting **customize**.
- At the bottom of the window, select **add from file**, browse to the location of the display.dll file and add it.
- A toolbar named **WRAP** is added to the Graphical User Interface, inside the toolbar a button named **GIS display** is included. When clicking it the tool itself shows up.
- The project should already include the shapefiles containing control points and reservoirs.
- The user first has to define the location of the WRAP output file and the BES file, as well as the layer containing the control points and the reservoirs.
- The different variables that can be displayed are shown in Table 6.1, after the user selects one variable, the different options enable or disable as necessary to collect the information necessary to display the results.

TABLE 6.1 Variables displayed in GIS

Variable		Appies to	Time scale
1	Percent of Storage	All Reservoirs	Monthly
2	Percent of Target met	All Control Points	Monthly
3	Volume Reliability	All Control Points	All simulation
4	Period Reliability	All Control Points	All simulation
5	Time series of naturalized streamflows	Control Point	Variable
6	Time series of regulated streamflows	Control Point	Variable
7	Time series of unappropriated streamflows	Control Point	Variable
8	Time series of reservoir storage	Reservoir	Variable
9	Time series of percent target met	Control Point & Water Right	Variable
10	Time series of streamflow depletions	Control Point	Variable

The first four variables use colors to display the result, the remaining six use a chart to display the selected time series. The classification of the results, including range and colors used is shown in Table 6.2. In the case of a value that does not apply to any of these ranges (such as a gage station), the color is white and the value assigned is -98.

TABLE 6.2 Colors used depending on the variable value

Value	Color
<50%	Red
50%-70%	Orange
70%-90%	Yellow
90%-95%	Light green
95%-100%	Green

6.3.1 Displaying the results

When displaying variables 1 or 2, the user should specify a specific month to display, while when using options 3 or 4, it is not possible to specify a date, since these variables take into account the results obtained for all the simulation.

For variables 5 to 10, the user should select individual control points, reservoirs or water rights, depending on the option. The user should also specify a starting and an ending date.

It is also possible to perform the analysis for the complete basin, in this case for naturalized streamflow (variable 5), regulated flow (variable 6) and unappropriated flow (variable 7), the quantities shown, represent the maximum flow at any control point in a given month, based on comparing all control points. On all other options, the quantities shown are the values at any control point, reservoir or water right.

Variable 1 creates a new field in the reservoir's attribute table named **pstor** containing the reservoir percent of storage that is being displayed. In a similar way variable 2 creates a field named **ptarget** in the control point's attribute table that contains percent of target met information for the specified month. Variables 3 and 4 create fields named **volrel** and **perrel** that contain volume and period reliability respectively.

In the case of time series, each time a time series is displayed, a text file containing the displayed data is created in the path where WRAP files are stored. These files may be easily exported into Microsoft Excel or any other graphing software in order to perform a more detailed analysis.

6.4 EXAMPLE

A simplified dataset for the Brazos River Basin was selected as a case of study, this dataset, contains 26 control points, 14 reservoirs and 128 water rights. This simplified basin captures the most important features from the original basin.

The tool was used to display the results in GIS, figures 6.1 to 6.12 display some screenshots of the results, for the different variables obtained during the analysis.

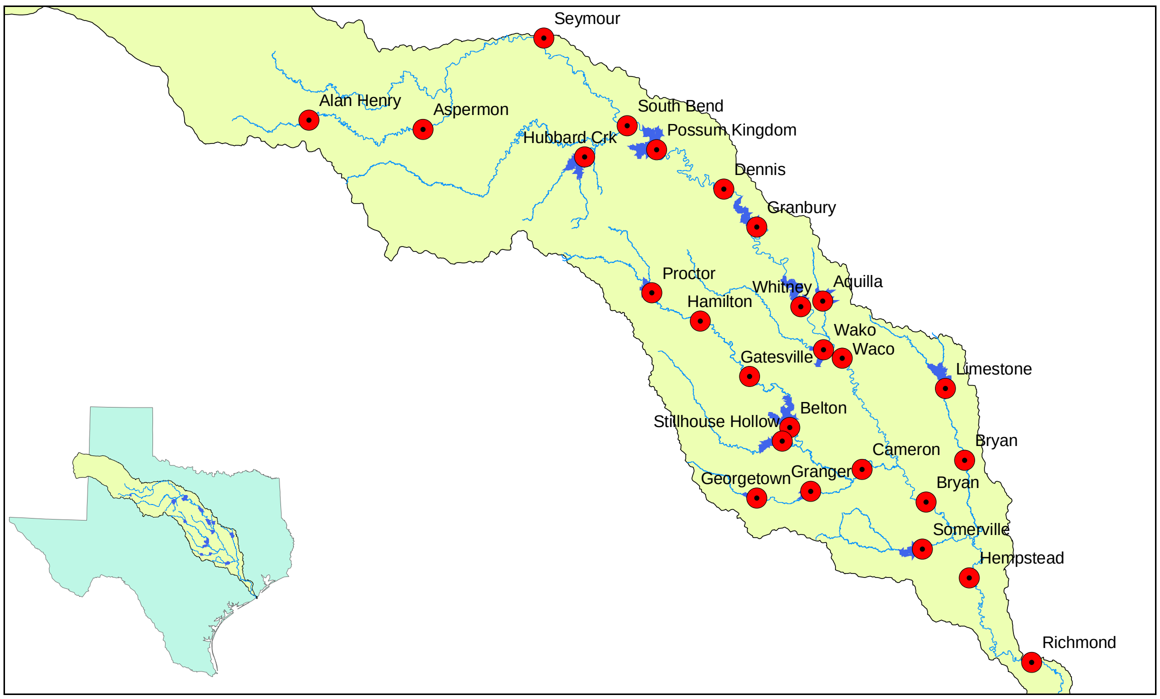


FIGURE 6.1 Simplified Brazos River Basin, Control points.

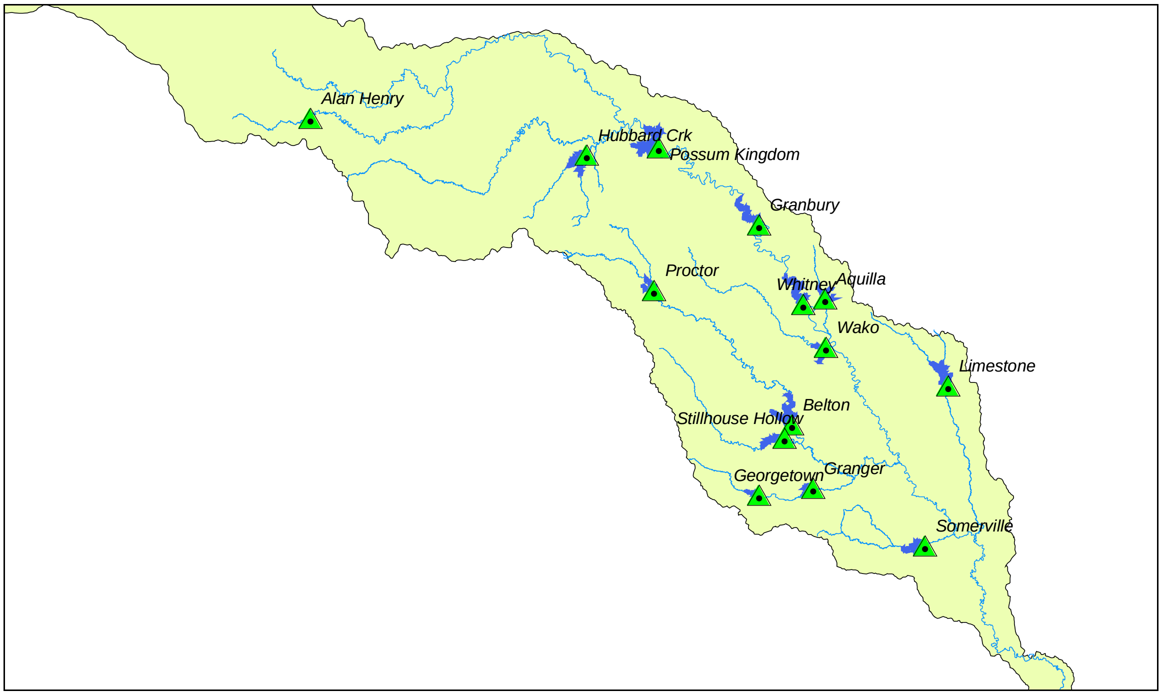


FIGURE 6.2 Simplified Brazos River Basin, reservoirs.

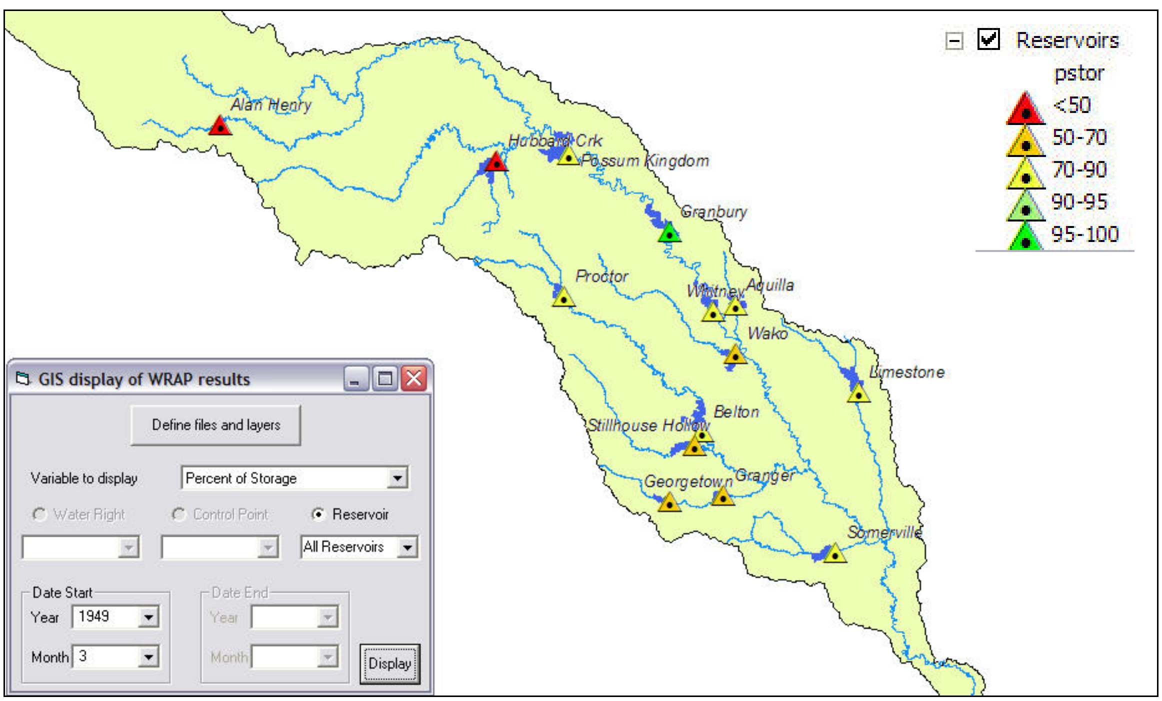


FIGURE 6.3 Percent of storage at each reservoir, March 1949.

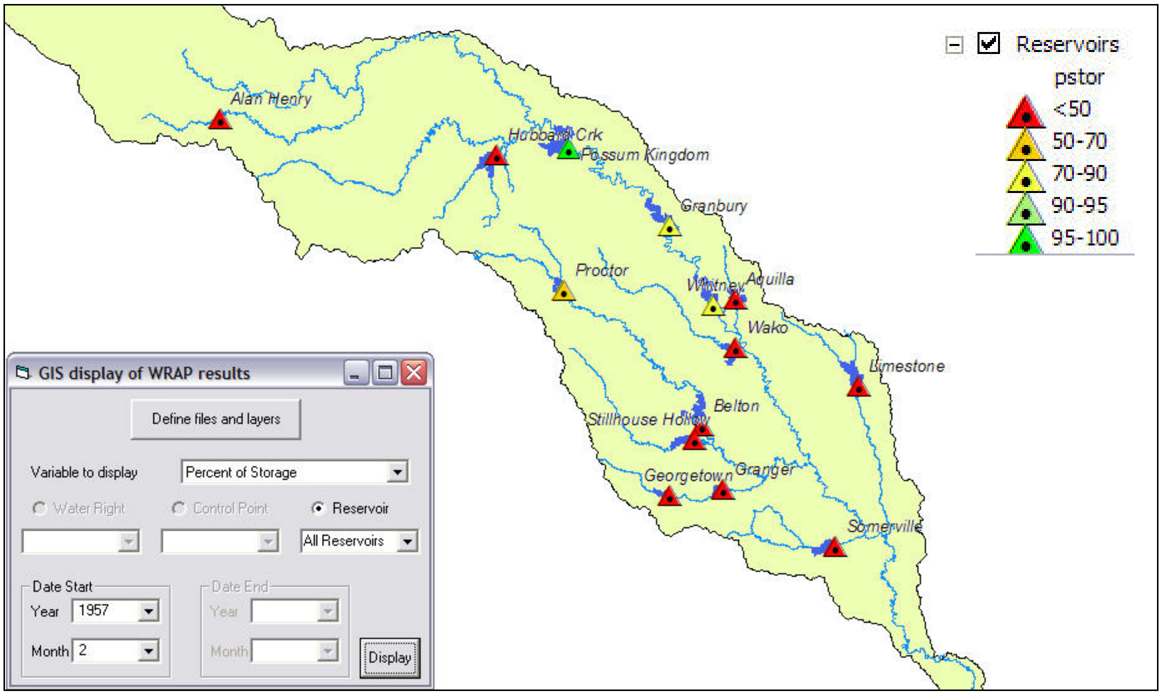


FIGURE 6.4 Percent of storage at each reservoir, February 1957.

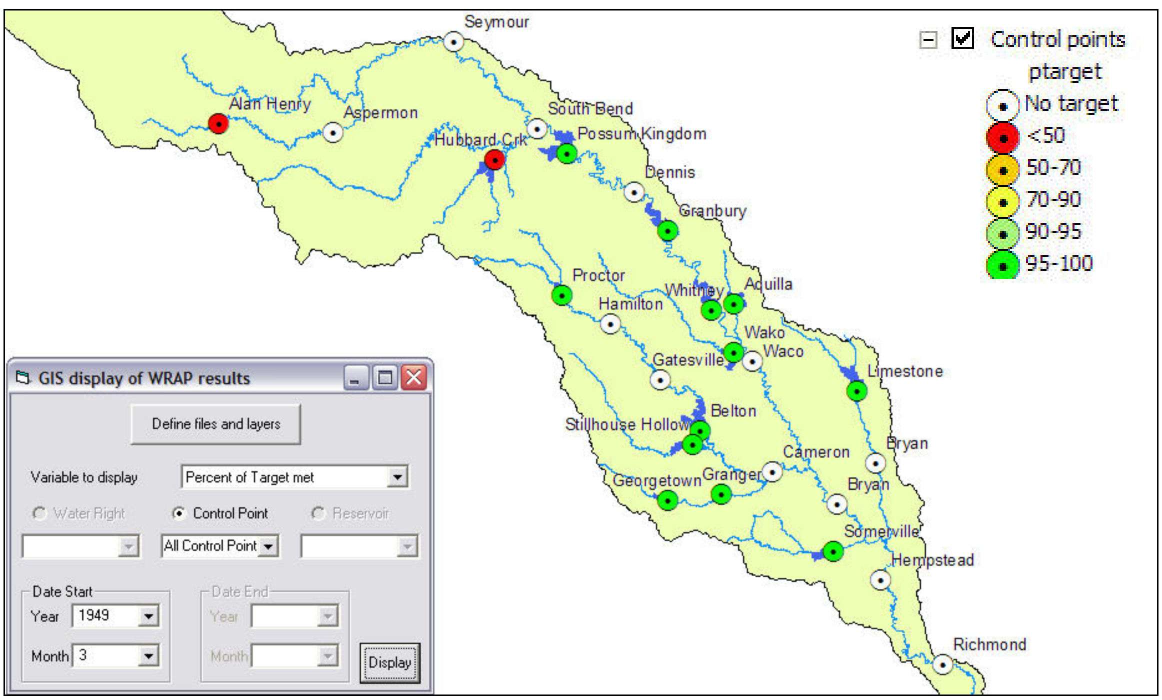


FIGURE 6.5 Percent of target met at each control point, March 1949.

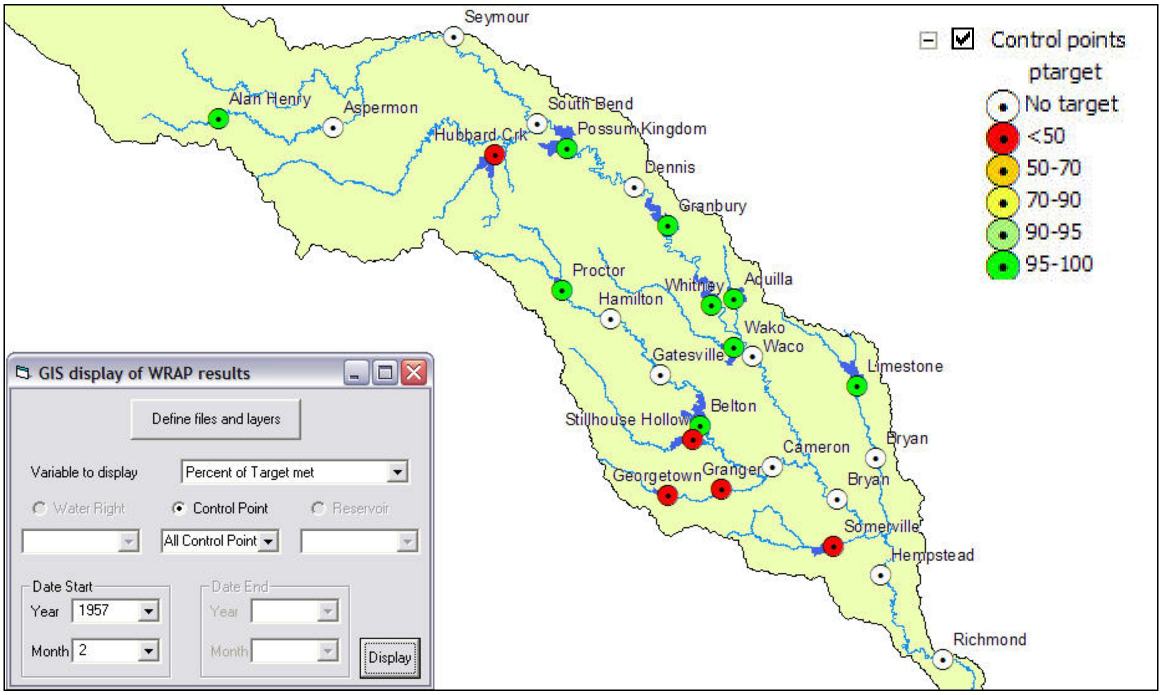


FIGURE 6.6 Percent of target met at each control point, February 1957.

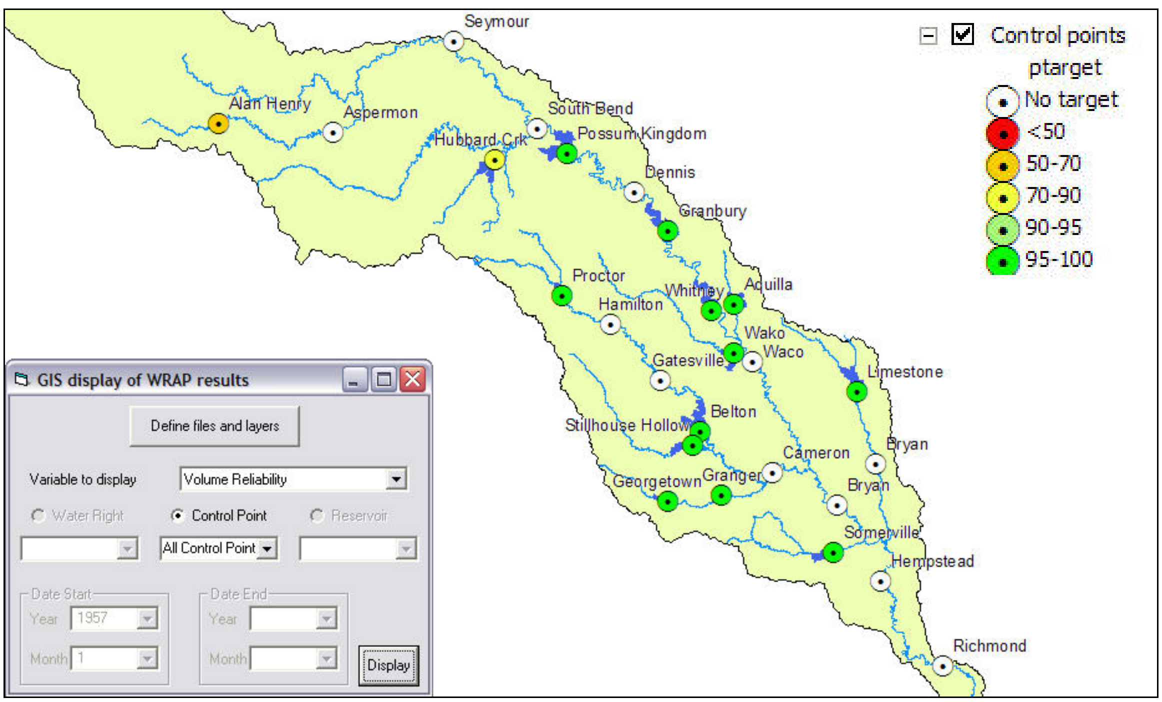


FIGURE 6.7 Volume reliability at each control point, entire simulation.

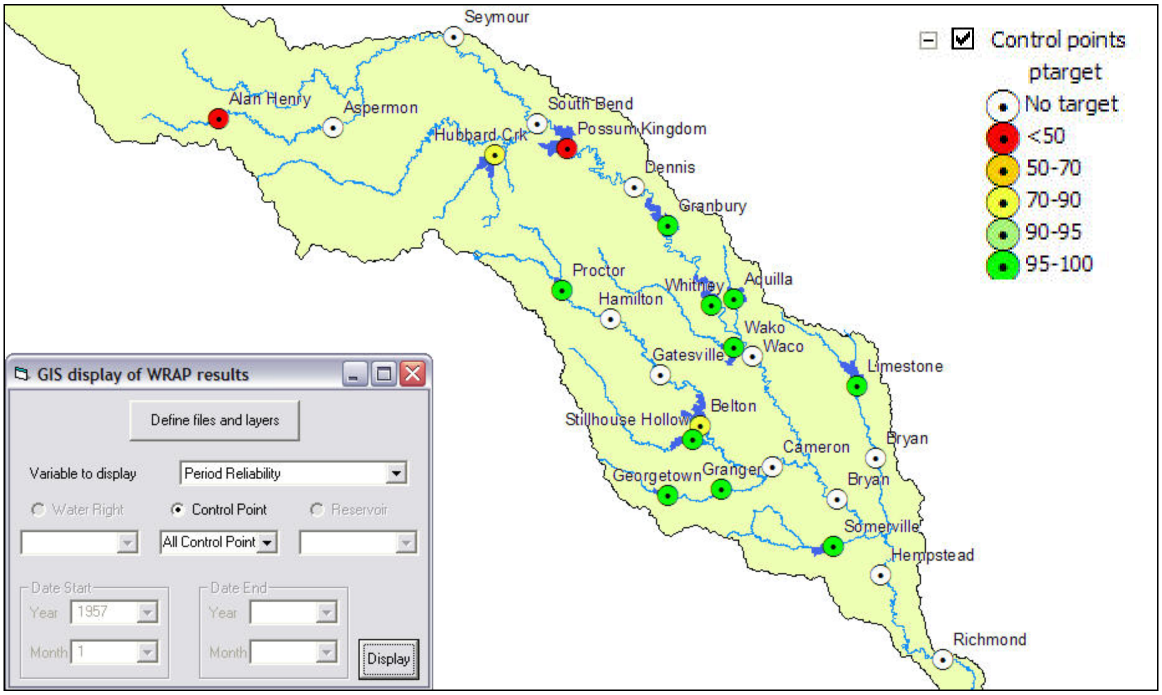


FIGURE 6.8 Period reliability at each control point, entire simulation.

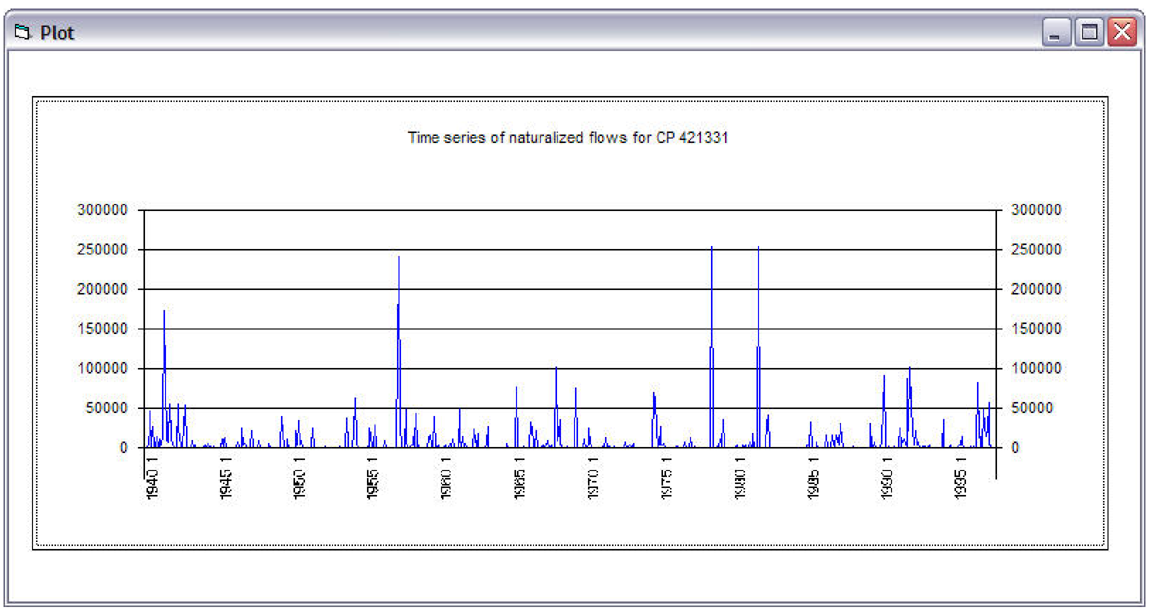


FIGURE 6.9 Time series of naturalized flow at control point 421331.

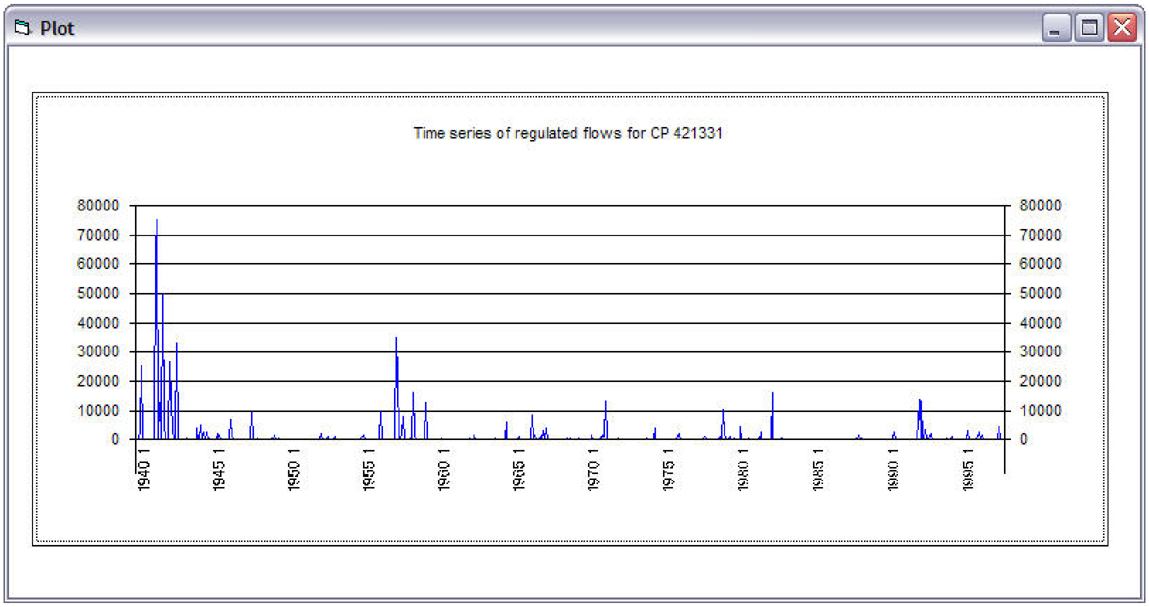


FIGURE 6.10 Time series of regulated flow at control point 421331.

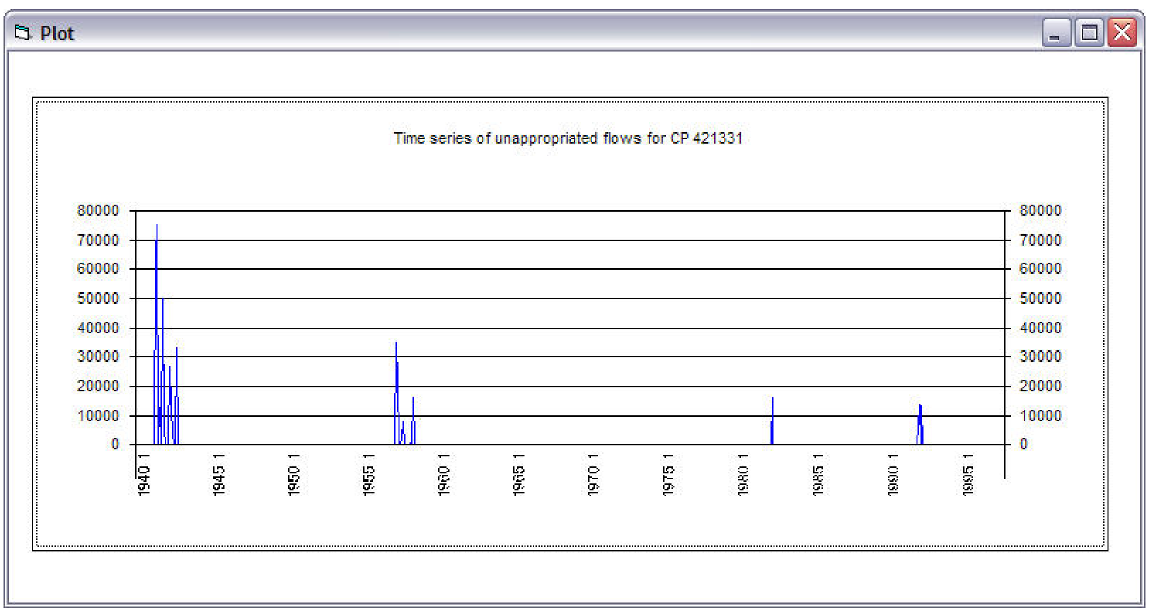


FIGURE 6.11 Time series of unappropriated flow at control point 421331.

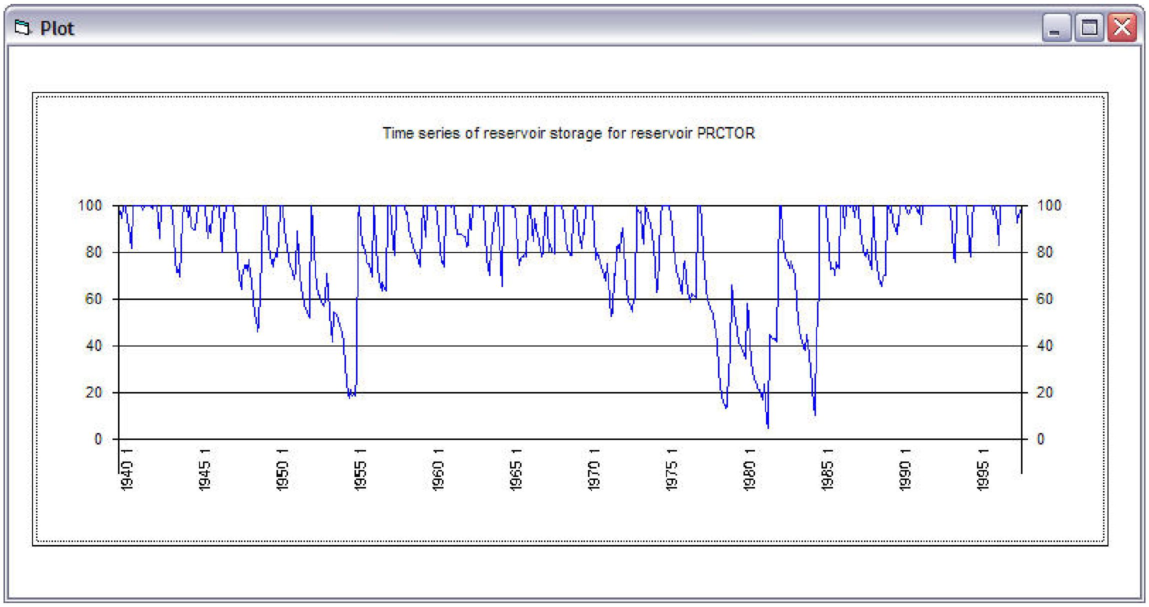


FIGURE 6.12 Time series of storage at Proctor reservoir.

6.5 COMMENTS

WRAP output files can be very voluminous, therefore it is recommended to include only those water rights, control points and reservoirs that are going to be displayed. Otherwise computer performance may be affected while doing the analysis.

This tool is the first step in developing a better interface to display WRAP results in a more friendly way.

It is important to notice that a graphical display of results can be very useful to capture aspects that wouldn't be noticed on a simple text file or a table. GIS is the appropriate tool to perform this analysis, since it can handle easily both, geographical information (Control point location) and a massive amount of data (WRAP output).

CHAPTER VII

SUMMARY AND CONCLUSIONS

This research developed and tested new methodologies for dealing with the issues in water availability modeling. These issues include: simplifying complex and voluminous WAM datasets, implications of different negative incremental flow options, estimation of yields for individual and multiple reservoirs, impact of initial storage on reliabilities and yields, conditional reliability modeling, and GIS display of simulation results.

7.1 SIMPLIFYING AN EXISTING WAM DATASET

Some of the Texas Water Availability Modeling (WAM) System datasets are extremely large and complex, which translates into practical difficulties when dealing with many applications. A methodology was developed to create a simple dataset with control points and reservoirs of interest, that would reflect the effect of all the other water rights in the basin. The results obtained from simulating the simplified dataset should be the same as those obtained when simulating the original dataset. This methodology was applied to the Brazos River Basin and more specifically to the Brazos River Authority system.

The main concept in this methodology is to consider only the water that corresponds to each control point or water rights and all unappropriated flows, in other words, water that was depleted by selected water rights during the simulation of the complete dataset, and water available for new permits.

Results showed that depending on the basin configuration, it is possible to have identical results, but some complexities were found when modeling reaches with extreme channel losses. In this case it was found that some downstream senior water rights were using the water that upstream junior rights depleted during the complete simulation. This was caused by the negative incremental naturalized flows option that was being used, with option 4 producing greater differences than option 5.

Some of the reservoirs and control points initially considered had to be removed in order to reproduce the full dataset results. These reservoirs were located in the upper part of the basin and the reasons why they had to be removed were discussed in chapter 3.

The simplified dataset may have several applications, such as:

- Calculation of firm yields at individual reservoirs
- Calculation of firm yields with reservoir operated as a system
- Testing of new modeling strategies

7.2 ESTIMATION OF YIELDS FOR INDIVIDUAL AND MULTIPLE RESERVOIRS

Reservoir yields were estimated for reservoirs belonging to the Brazos River Authority system. These reservoirs were simulated as individual reservoirs or as a system of reservoirs. Different scenarios were modeled, including the construction of Allens Creek reservoir in the lower basin.

Multiple methodologies to calculate yields were used, and comparisons between results were made. Some methodologies had already been used in previous studies and some were developed for this study, including the use of the simplified dataset to compute reservoir yields.

Results showed that if reservoirs are operated individually, the construction of Allens Creek reservoir increases the total yield by 10%, but if the existing reservoirs are operated as a system, yields increase by the same amount if the use of unregulated flows is restricted. If the use of unregulated flows is allowed and reservoirs are operated as a system, yields can increase up to 45% compared to existing individual reservoirs. These results show the benefits of operating reservoirs as a system and the economic benefits that it can provide, since the construction of reservoirs has a high economic and environmental cost.

When calculating reservoir yields, following a priority order, it was found that yields are highly affected by the stopping criterion and by the fact that some reservoirs have demands greater than the individual reservoir's firm yield calculated previously.

Therefore the yield calculated using a priority order was about half the one calculated using individual reservoirs.

The use of a new feature in WRAP known as the dual option is useful in situations where multiple water rights with different priorities are associated with the same reservoir. In the case of issuing a new right permit, this right would be junior to all existing rights and should not affect reliabilities on any other rights in the basin. But since it is receiving water from a reservoir that has other senior rights, the new right will decrease the storage level at a junior priority, but storage will be refilled at the most senior priority of the rights located at the reservoir with other rights in the basin being affected by the new right. This new option was compared to those results obtained when using the simplified dataset, and it was concluded that both methodologies produce similar results with differences of around 1%.

Recently, the Brazos River Authority applied for a system permit to divert water at the Gulf of Mexico. Freese and Nichols on behalf of the BRA developed a modeling strategy to calculate the diversions as a result of operating all reservoirs as a system and considering the impact of all other water rights in the basin. Results obtained by Freese and Nichols's approach were compared to those obtained with the dual simulation, finding that both methodologies produce almost the same result.

Interruptible yields are yields that are not available 100% of the time, and therefore are subject to shortages. They are obtained by reducing the firm yield on a reservoir or a system of reservoirs, and establishing a reservoir storage level below which no releases for interruptible yields are made. This source of water is suitable for purposes that do not require 100% reliability, such as irrigation rights. Interruptible yields at the Gulf of Mexico were calculated for the BRA system, reducing the system firm yield by 10 or 20%. Results show that interruptible yields are considerably higher than the amount by which firm yield is reduced, with this additional water it is possible to issue new water rights that exclusively use these interruptible flows, that otherwise would flow into the Gulf of Mexico without being used.

7.3 IMPACT OF BEGINNING STORAGE ON RELIABILITIES AND YIELDS ESTIMATES

7.3.1 Reliabilities

The assumption of having reservoirs starting full at the beginning of the simulation may not be correct in all cases. The impact that beginning storage has on reliabilities and reservoir yields was evaluated by using a new WRAP capability that carries out cycling. Cycling performs a second simulation where storages at the end of the first simulation become the storages at the beginning of the second simulation.

By performing simulations for the Brazos River Basin and the Guadalupe and San Antonio Basins, it was found that when using cycling, reliabilities for around 20% of the water rights in the Brazos River Basin and 30% of the rights in the Guadalupe and San Antonio Basins were negatively affected. For these simulations, the initial years of the period of analysis were wet years, so it is believed that the effect of not starting with the reservoirs being full is lost during the first months.

The datasets were modified to start the simulation in 1950, which was the starting year of the worst drought in record that ended in 1957. Results show that the number of affected rights and the magnitude of the differences is higher than when having wet years at the beginning of the simulation.

7.3.2 Yields

In order to evaluate the impact of the initial storage on the firm yield estimate for the Brazos River Authority system, cycling was applied to the simulation. Results showed that the firm yield estimate is not affected; this is explained because most of the reservoirs included in the system finish the initial simulation with high storages, which are easily refilled during the first months of the second simulation.

As done for the reliability analysis, the simulation was modified to start in 1950, finding that the firm yield was slightly less than the yield obtained with reservoirs starting full.

7.4 CONDITIONAL RELIABILITY MODELING

Conditional Reliability Modeling is a technique used to estimate short term reliabilities and frequencies, conditioned on preceding reservoir storage. In order to do so, the hydrologic period of analysis of a long term simulation is divided into multiple short term sequences and each sequence is simulated starting always with the same initial storage.

A long term reliability analysis such as the one performed by WRAP, assumes all reservoirs start the simulation full or may adopt a cycling option in which end of simulation storages become initial storages for a new simulation. This long term reliability does not reflect the fact that reservoir managers know current storage levels, something crucial when determining reliabilities a few months into the future. If a reservoir is 80% full, the likelihood of being full in 6 months into the future is greater than if it is 20% full now.

A typical long term simulation with a period of analysis from 1940-1997 can be divided into 58 annual sequences, or 696 monthly sequences. The system is simulated 58 or 696 times with equal number of different naturalized streamflow and net evaporation sequences, with each simulation sequence having a fixed initial reservoir storage level. Reliability estimates are developed from the simulation results.

Two different Conditional Reliability models were used in this study, the conditional reliability using Conditional Frequency Duration Curve model and the conditional reliability using a Storage-Flow frequency array.

7.4.1 Conditional Frequency Duration Curve model

This model assigns probabilities to naturalized flows based on a Conditional Frequency Duration Curve (CFDC) developed for specified storage intervals. In order to develop a CFDC, it is necessary to execute a long term simulation with the conventional WRAP to obtain the storage series that would occur with the repetition of historical natural flows. Then, the storage capacity is divided into several intervals representing different levels, i.e. High, medium, and low storage. The naturalized flow series is divided into equal number of intervals, having one array of flows for each storage level. Each array of flows contains the flows that followed the occurrence of each storage level. A statistical analysis using the Weibull formula assigns probabilities to each naturalized flow given the occurrence of a storage level.

After developing the CFDC and running the different initial storage conditions, it is possible to compute conditional reliability of storage and diversions. . In the case of storages, reliabilities are calculated for the last month of the period of analysis. In the case of diversions, reliabilities are calculated for the entire period of analysis as the sum of diversions made divided by the sum of diversion targets. Naturalized flows are also cumulated over the period of analysis and an array containing either storage or cumulated diversions and the cumulated flows over the period of analysis is built. It is assumed that a higher flow will produce an equal or greater diversion amount, therefore, the probability of equaling or exceeding the computed storage or average diversion amount is equal to the probability of equaling or exceeding the corresponding cumulated naturalized flow. This probability is obtained from the CFDC.

In order to correctly assign probabilities to diversions or storage values, it is necessary to develop a naturalized flow-diversion or storage relationship, where for each value of naturalized flow there is a unique value of diversion or storage. This relationship is developed by using two different regression techniques, linear and S-curve regressions. The selected regression is applied to the naturalized flows and a unique relationship between naturalized flows and diversion/storage is found.

The CFDC modeling technique is highly dependant on the autocorrelation of flows. If flows are autocorrelated, a future flow may be derived partially from previous flows. If flows are not autocorrelated, it may not be possible to develop a meaningful CFDC, and the assumption of any flow sequence having the same probability of occurrence may be as accurate as the CFDC technique.

Methodology to apply the model

The recommended methodology to apply the model is the following:

- The use of cycling is recommended when performing the long term simulation, since the effect of the initial storage, may affect the CFDC.

- Calculate the correlation between storage in major reservoirs and future naturalized flows for the control points of interest. Those reservoirs showing a good correlation should be selected to develop different reservoir combinations.
- A new correlation analysis is done for each reservoir combination and those showing a good correlation are selected to develop a CFDC.
- A CFDC is developed for each one of the selected reservoir combinations; each CFDC is analyzed to check that the naturalized flows increase with the storage content. The CFDC that offers the best behavior is selected.
- The short term reliabilities are calculated by using the selected CFDC and the conditional reliability simulation results.

Conditional reliability analysis for Lake Waco

A conditional reliability analysis was done for Lake Waco, 8 different initial storage conditions were simulated and storage and diversion reliabilities were calculated for 1, 3 and 6 months into the future, starting in January.

Four different reservoir combinations were used, in order to evaluate the impact of a reservoir combination in the final results.

Results show that the three reservoir combinations with high correlation between storage and flows give almost identical results. But the reservoir combination with a relatively lower correlation generated considerable differences in reliabilities.

With the exception of high initial storages on the 6 months analysis, reliabilities increased with initial storage, as it is expected. It was found that the reliabilities decreased with storage for the 6 month analysis, because it was not possible to establish a good regression between naturalized flow over the 6 months and storage at the end of month 6, this can be identified because of the low R^2 value for those reliabilities.

Comparison with the equally likely model

While flows are autocorrelated, the model produces different results from those obtained from the equally likely model. For low storage conditions, the reliabilities obtained from the CFDC model are lower than those obtained from the equally likely one. This is explained because under low storage conditions, low flows are more likely to occur than high flows. As the initial storage is increased, the reliabilities obtained with the CFDC approach increase and eventually exceed the equally likely reliability values, since with high storage conditions high flows are more likely to occur.

7.4.2 Storage Flow Frequency model

The Storage Flow Frequency (SFF) methodology is similar to the CFDC one, in the sense that it divides a long term simulation into multiple short sequences, but the way probabilities are assigned to each sequence is completely different.

The SFF option to assign probabilities to each sequence is based on the relationship between storage-flows and frequency. A variable storing the ratio between flows and expected flows, measures the deviation of the flow volume from the expected value of the flow volume, depending on initial storage.

Four different regression equations can be used to relate naturalized flow volume and preceding storage volume, these are: exponential, linear, power and combined; with the exponential being the default option.

After reading the initial storage volumes and naturalized flow volumes from the long term simulation, the selected regression is applied and its coefficients representing the relationship between storage and flows are obtained. It is expected that flow volumes increase wit storage. The expected value of flow conditioned on storage is computed for each simulation sequence using the derived regression coefficients, and the corresponding values of the ratio between flow and expected flow are determined. Exceedance probabilities are assigned to each ratio by applying either the Weibull or the Log-Normal probability distributions.

Once the SFF array has been created, it is necessary to assign incremental probabilities to each simulation sequence from a CRM simulation. The procedure used is as follows:

The naturalized flows in each month of the sequences are read from the conditional reliability simulation output. Then initial storages are read for the pertinent reservoirs and are accumulated to obtain the total initial storage amounts. Naturalized flows over the specified months are also summed to obtain the total flow amounts for each sequence.

The expected flow value is calculated based on either regression coefficients computed when developing the SFF relationship or user defined values, and ratios between cumulated flows and expected flow values are determined. The ratios obtained are linearly interpolated within the SFF array, to obtain an exceedance frequency for each ratio (sequence).

The ratios are ranked in order and their corresponding exceedance frequency is converted into incremental probabilities. This incremental probability is computed based on the half-way points between the exceedance probabilities of that ratio and the next larger ratio and next smaller ratio. As a result of this process, incremental probabilities are assigned to each conditional reliability sequences; the total sum of these incremental probabilities is 1.

Reliability and frequency analyses are performed by applying a weight to each one of the many sequences in a CRM simulation, this weight is the incremental probability for each sequence. With it, it is possible to reflect the fact that some sequences are more likely to occur than others.

Methodology to apply the model

The recommended methodology to apply the model is similar to the one for the CFDC model:

- The effect of the initial storage in a long term simulation has to be removed, in order to do so, it is recommended to use cycling.
- A correlation analysis between storage in major reservoirs and future naturalized flows in the control point of interest. Those reservoirs with the highest correlation values should be selected for a reservoir combination analysis.
- A new correlation analysis between storage and future naturalized flows has to be done. This time storage corresponds to the different reservoir combinations created with the previously selected reservoirs. The reservoir combination with the highest correlation values is selected. It is recommended to perform the conditional reliability analysis with additional reservoir combinations.

- There are two cycling options, annual and monthly; for regions where flows vary greatly with seasons, it is recommended to use an annual cycle since all the simulations reflect the same season of the year. A monthly cycle considers all the months in the simulation, so it should only be used in a region with no seasonality.
- The number of months used to sum flows, depends on the number of months used to perform the CR simulations. In addition, if the correlation between storage and flows for a certain number of months is low, then it is recommended to use a smaller number of months in the analysis.
- Two probability distributions may be applied to the SFF, Weibull and Lognormal. Weibull distribution assigns exceedance probabilities based solely on the rank for each ratio; higher values of ratio have lower exceedance probabilities while lower values have higher exceedance probabilities. Lognormal Distribution assigns exceedance probabilities based on the mean and standard deviation of the ratios; it applies the normal distribution to the logarithms of the random variable, the normal probability density function is a bell shaped and symmetrical about the mean. Many hydrologic variables show a marked skewness, since physically they cannot be negative, this probability distribution assigns a zero probability to any negative value.
- There are 4 different regressions to develop the storage-flow relationship. These are exponential, combined, linear and power regressions. The default regression is the exponential.
- If it is not possible to obtain satisfactory results with the previous regressions, when considering all storage-flow values, then it is possible to establish storage integrals, to perform the analysis for a certain range.
- The probabilities for each sequences are calculated from the previously developed SFF array, it is recommended to use the same parameters adopted when developing the SFF array.
- Computation of reliabilities is done by using a 2REL record, for water supply diversions or hydroelectric targets, and a new 2SRL record for storage reliabilities.

Conditional reliability analysis for Lake Waco using SFF model

The same analysis done for Lake Waco using the CFDC model was done using the SFF approach. Four different reservoir combinations were used, in order to evaluate the impact of a reservoir combination in the final results.

Results show that when using the Weibull distribution to develop the SFF array, reliability values obtained for different reservoir combination have significant differences, and in some cases the trend obtained varies from combination to combination. While when using the lognormal distribution, these differences decrease, the trend is the same and the reliability curve is smoother than the one obtained using Weibull.

Differences between both distributions are as high as 10% for one month, and decrease with time, 6% for 3 months and 4% for 6 months. There is not a generalized behavior, but in most cases, when having low initial storage levels, lognormal distribution gives higher reliabilities. For high initial storages, there is no noticeable trend and sometimes Weibull produces higher reliabilities than lognormal or vice versa. For both distributions, results show that the expected reliability increases with initial storage.

Comparison with the equally likely model

As it occurred for the CFDC model, the equally likely approach predicts higher reliabilities than the SFF model when the initial storage conditions are low. There is a value of initial storage for which both models produce similar reliabilities. When considering high initial storage conditions, the SFF model produces higher reliabilities than the equally likely, since high storages are more likely to occur than average flows.

7.4.3 Comparison between CFDC and SFF models

An evaluation of the reliabilities obtained from both models was done. It was found that the SFF model is more conservative for low storage conditions, while for high storage conditions it produces a higher reliability. Differences in reliabilities are considerable, being as high as 37% when the reliability curve from the CFDC model had a high R^2 value or as much as 50% for a low R^2 value.

These differences can be somehow explained by the fact that when building a CFDC, all the months in the long term simulation are considered, without distinction of seasons; while when applying the SFF model, it is possible to select between an annual cycle or a monthly cycle, with the annual cycle considering only the same period for every year.

It was also found that the CFDC model did not work as expected for a reservoir with low fluctuations in storage. Lake Waco remained with a high storage most of the time, so a reservoir storage is considered low it is below 80%, and high if it is above 96%, this distribution does not seem to be even. It is expected that on a reservoir with high variations in storage, the storage levels on the CFDC are evenly distributed.

The SFF model seems to be a good alternative to the CFDC model, but it is recommended to use both models and compare results, in order to have a better estimate of reliabilities and basin behavior.

7.5 GIS DISPLAY OF WRAP RESULTS

A simple tool to display WRAP results into ArcMap 8x or higher was developed. This tool reads the output file generated by WRAP and performs computations to calculate some of the parameters calculated by TABLES and displays them with colors or as a time series within ArcMap.

The tool is a .dll file that can be imported into ArcMap. Once loaded, it displays a simple window in which the user selects the corresponding shapefiles for control points and reservoirs; the user also has to specify the location of the output file and an additional file containing information regarding reservoir capacities.

The use of a graphical interface to display results is very convenient for the user, and can show results in a more meaningful way than when displaying them in a table.

Although this tool is very basic, it can be the beginning of the development of a much more powerful GIS interface to display WRAP results.

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APPENDIX A

RESULTS FOR THE CONDITIONAL RELIABILITY MODEL USING A CFDC APPROACH

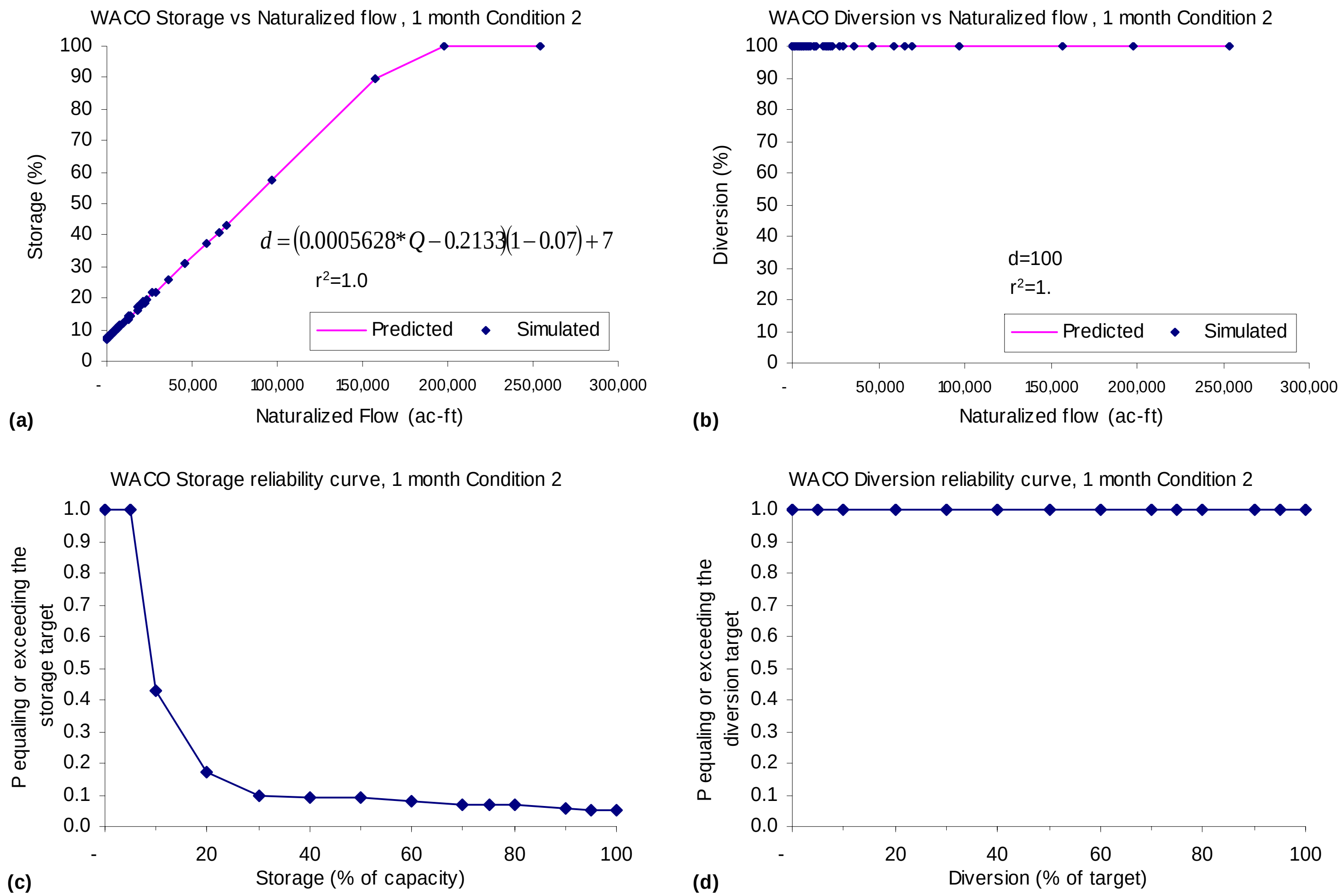


FIGURE A.1 Condition 2 simulation results for Lake Waco for 1 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

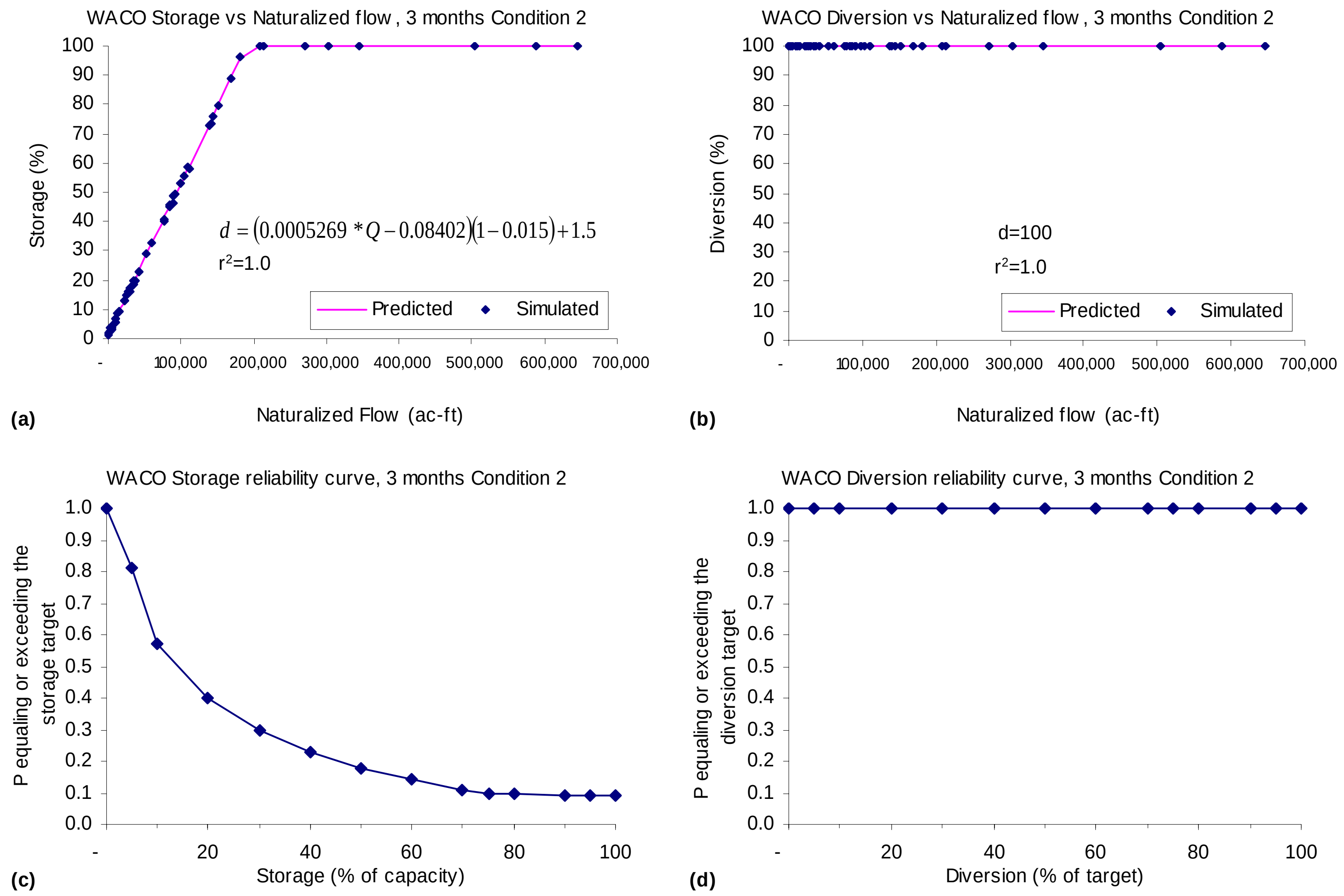


FIGURE A.2Condition 2 simulation results for Lake Waco for 3 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

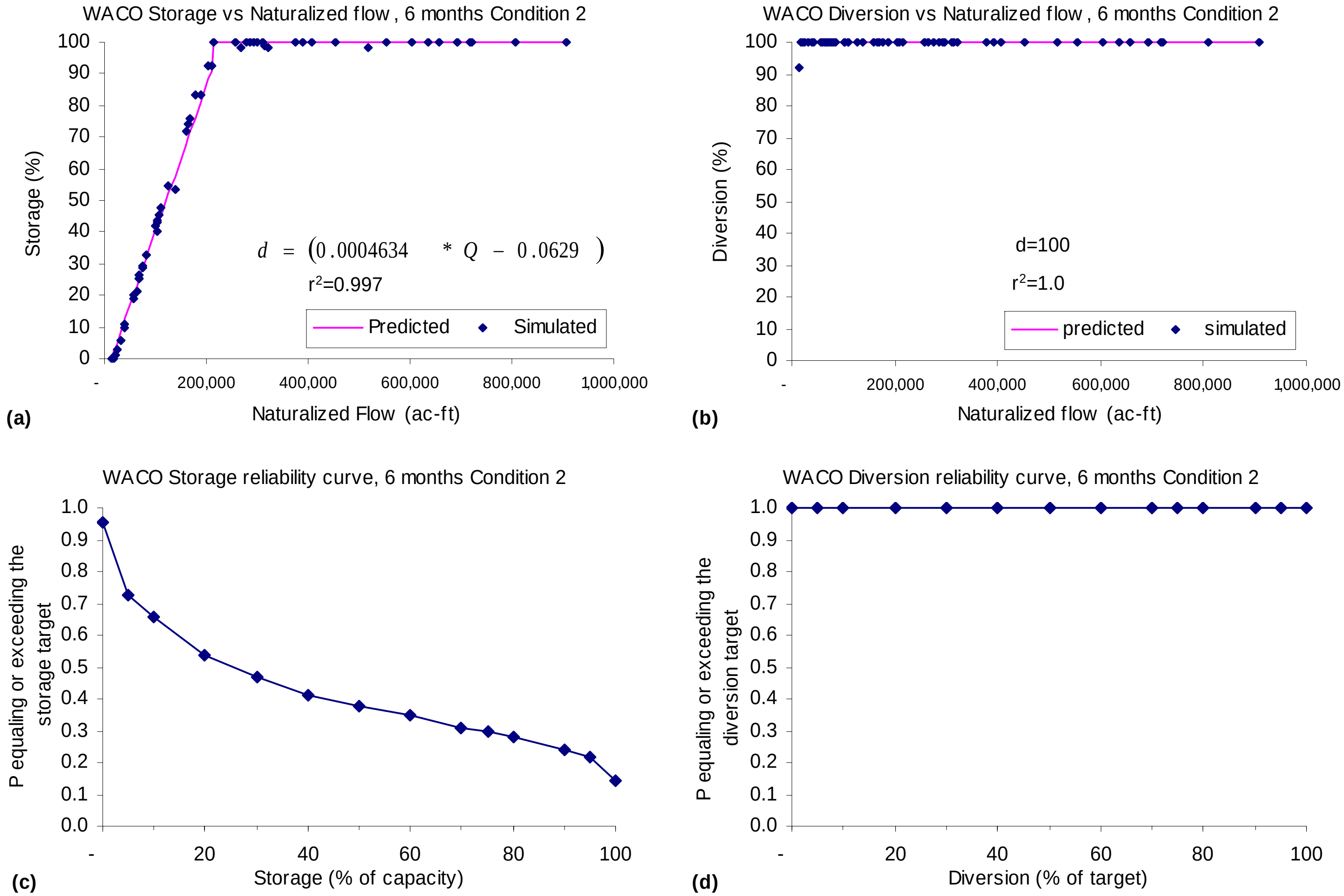


FIGURE A.3 Condition 2 simulation results for Lake Waco for 6 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

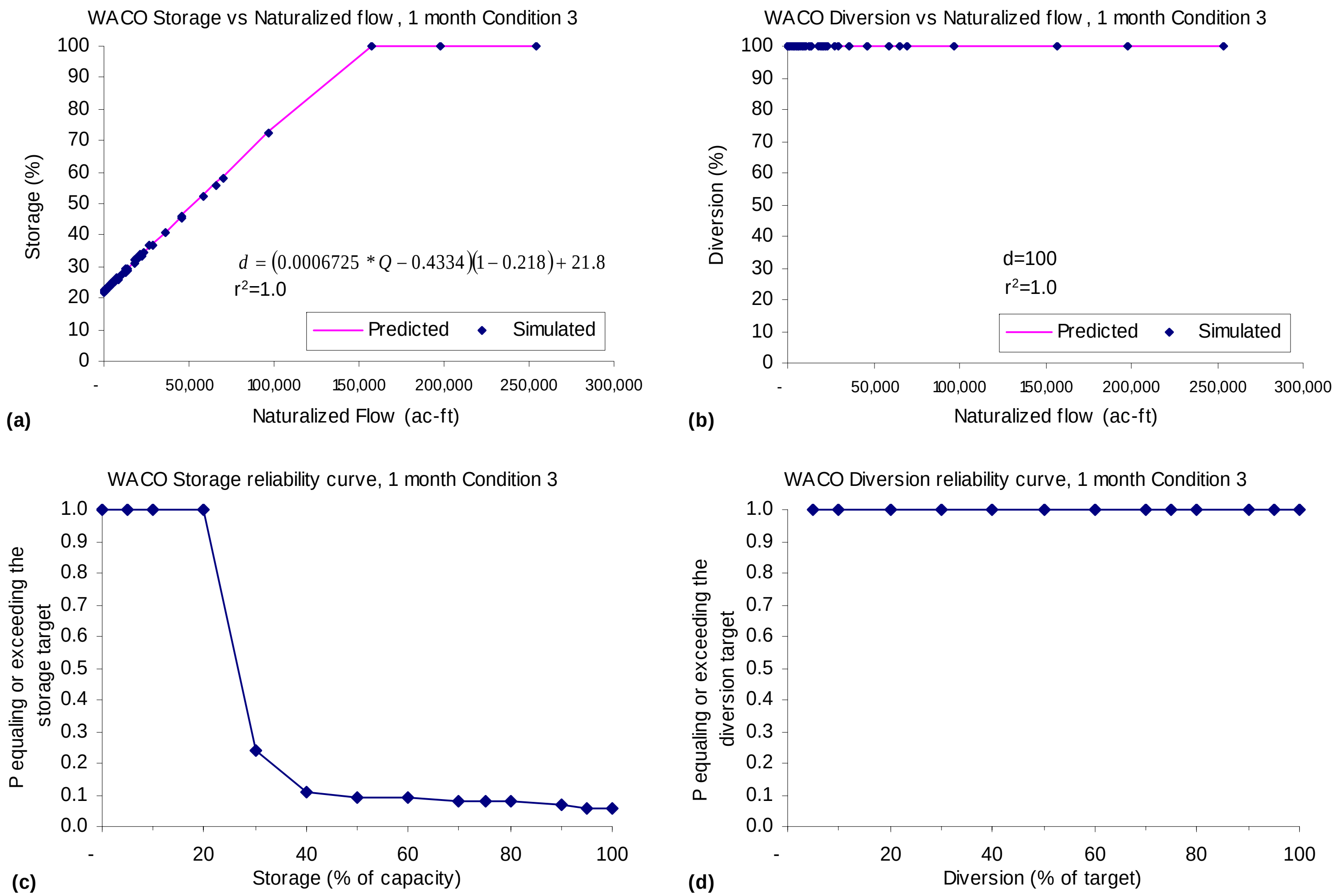


FIGURE A.4 Condition 3 simulation results for Lake Waco for 1 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

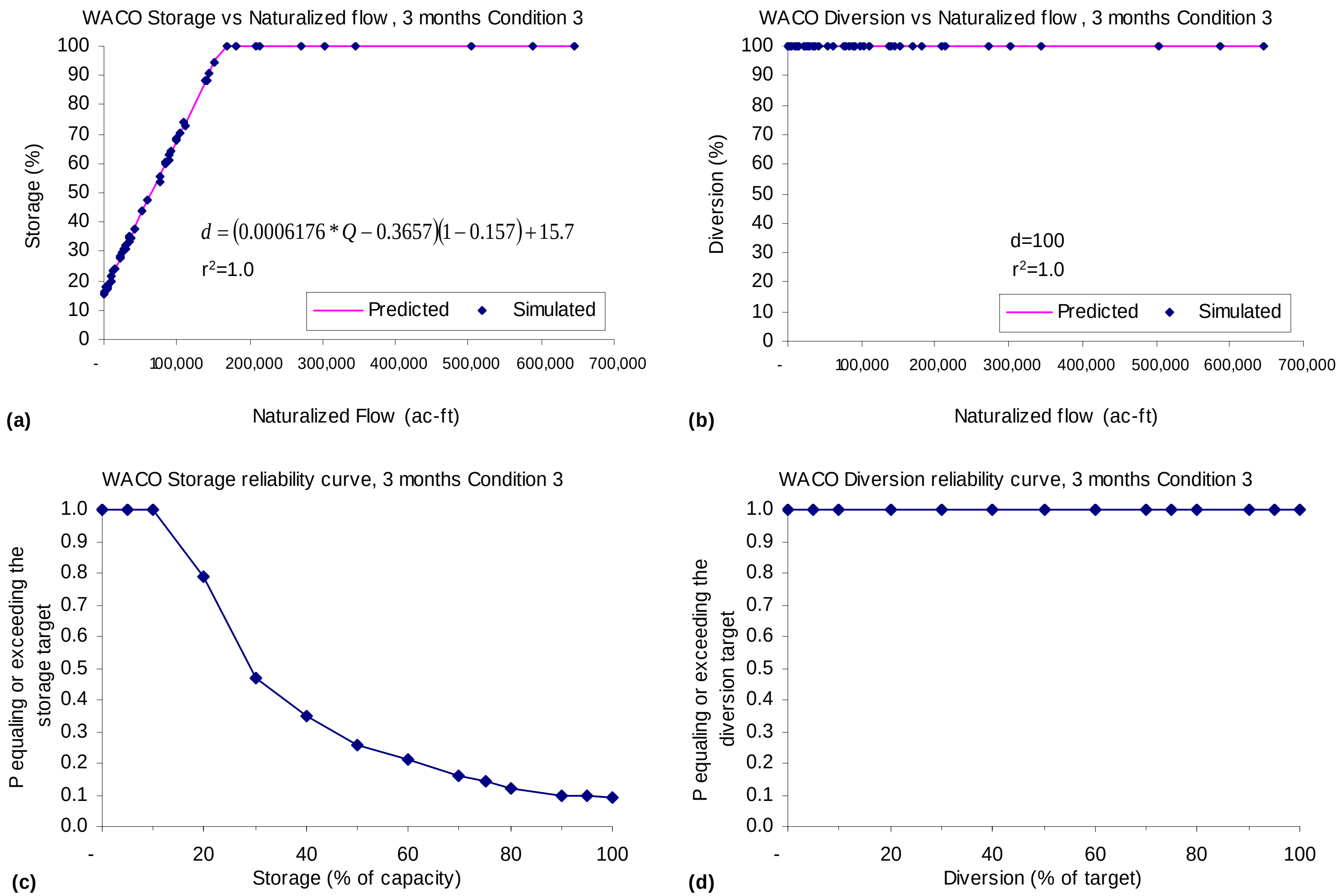


FIGURE A.5 Condition 3 simulation results for Lake Waco for 3 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

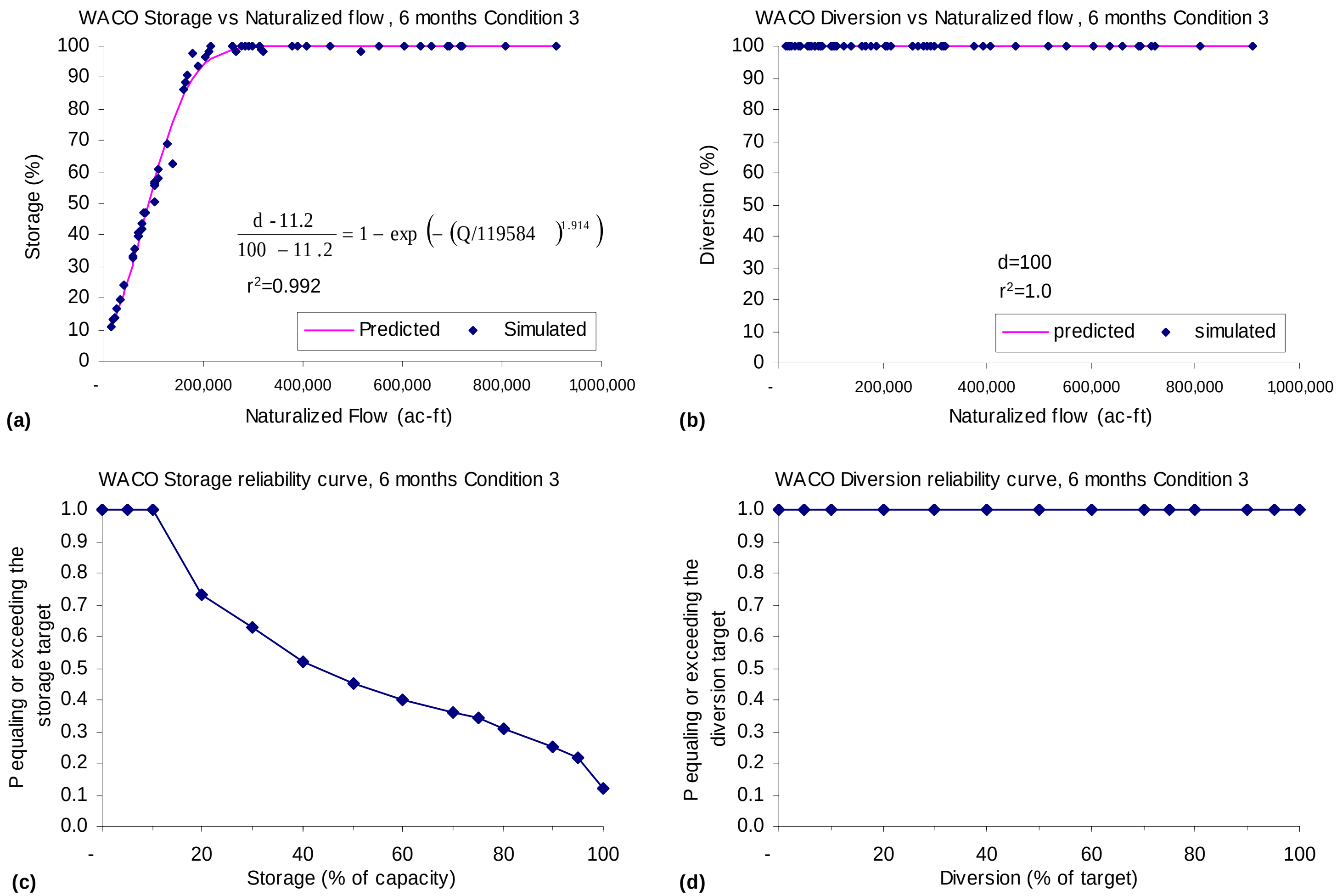


FIGURE A.6 Condition 3 simulation results for Lake Waco for 6 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

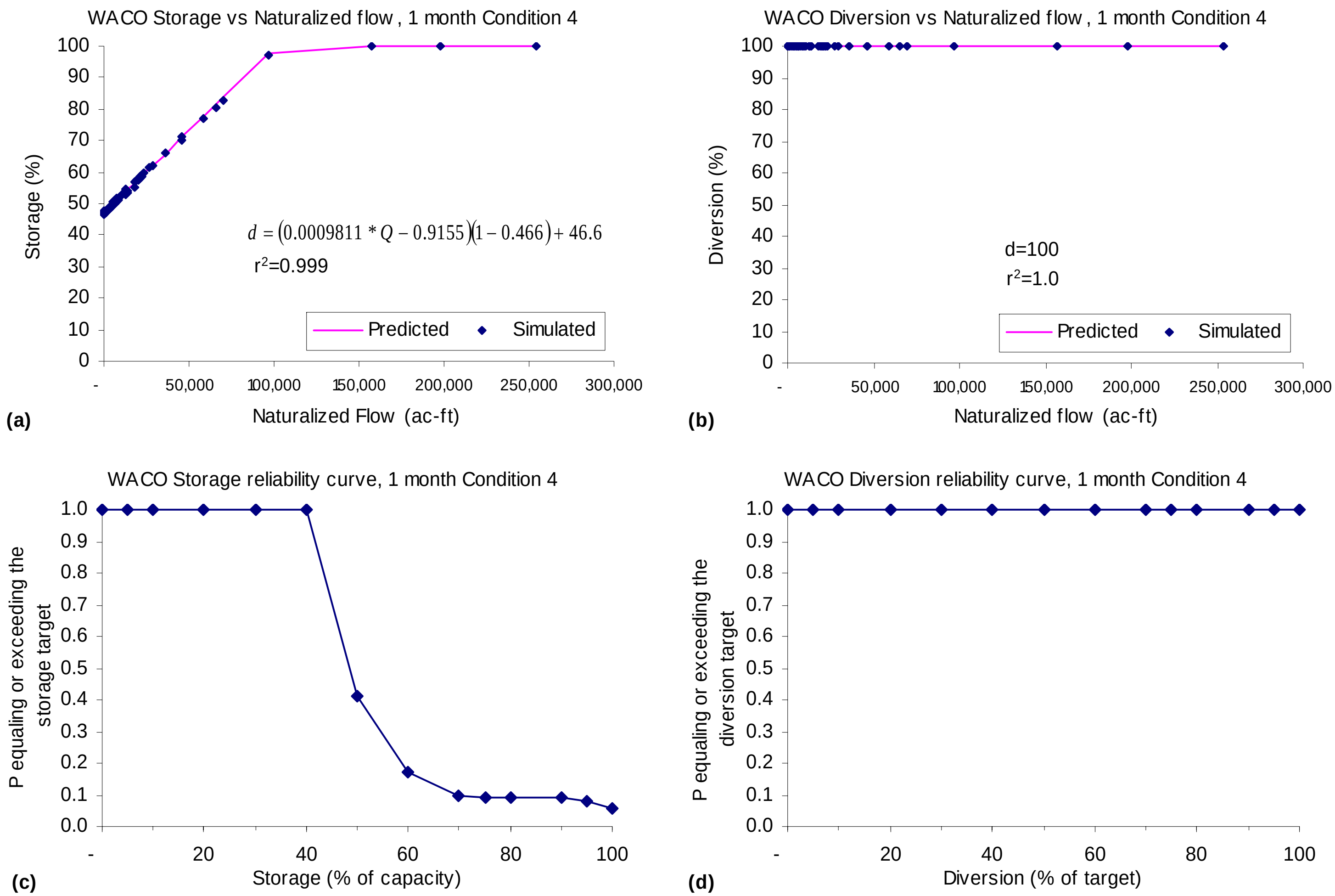


FIGURE A.7 Condition 4 simulation results for Lake Waco for 1 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

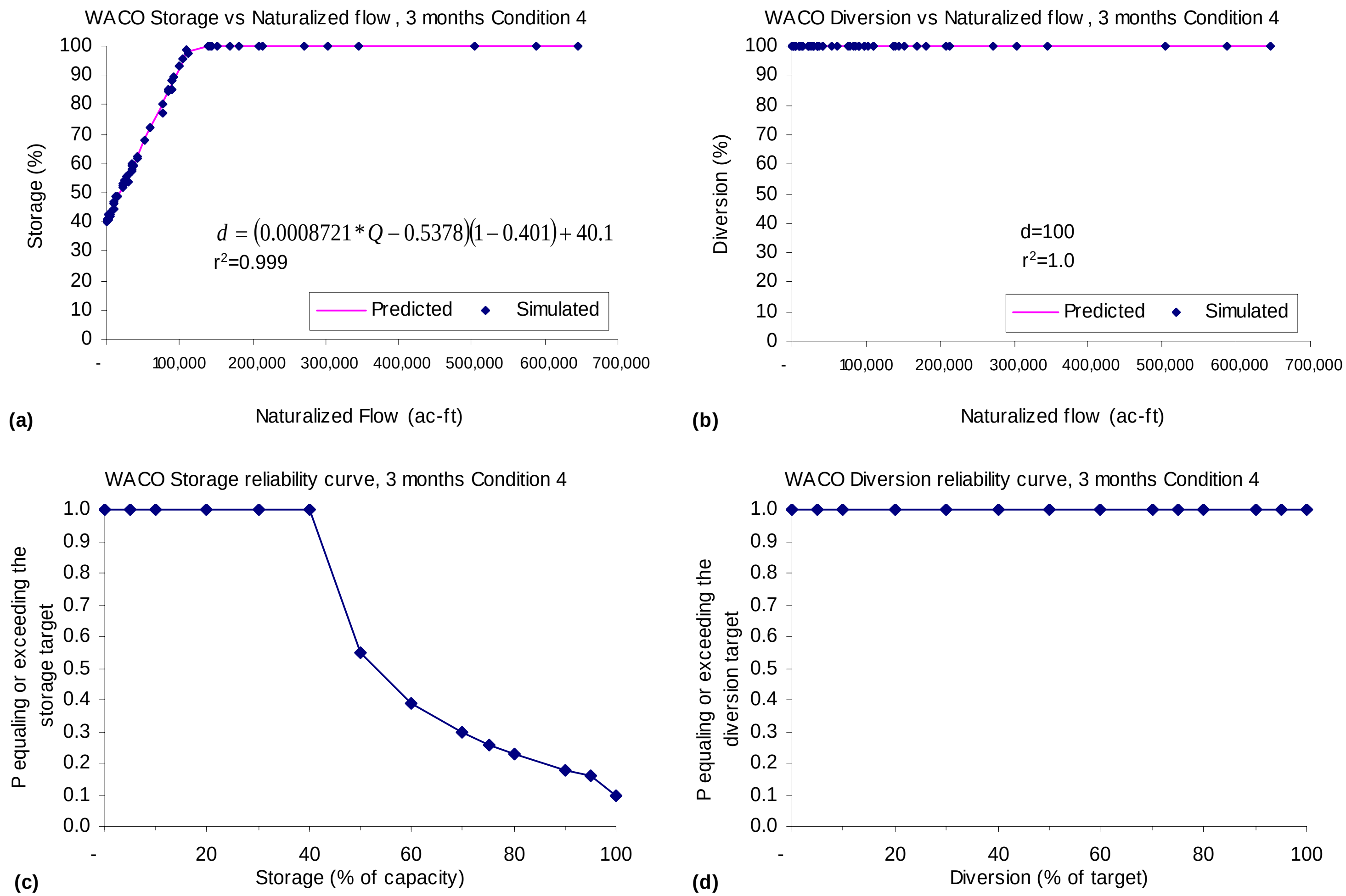


FIGURE A.8 Condition 4 simulation results for Lake Waco for 3 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

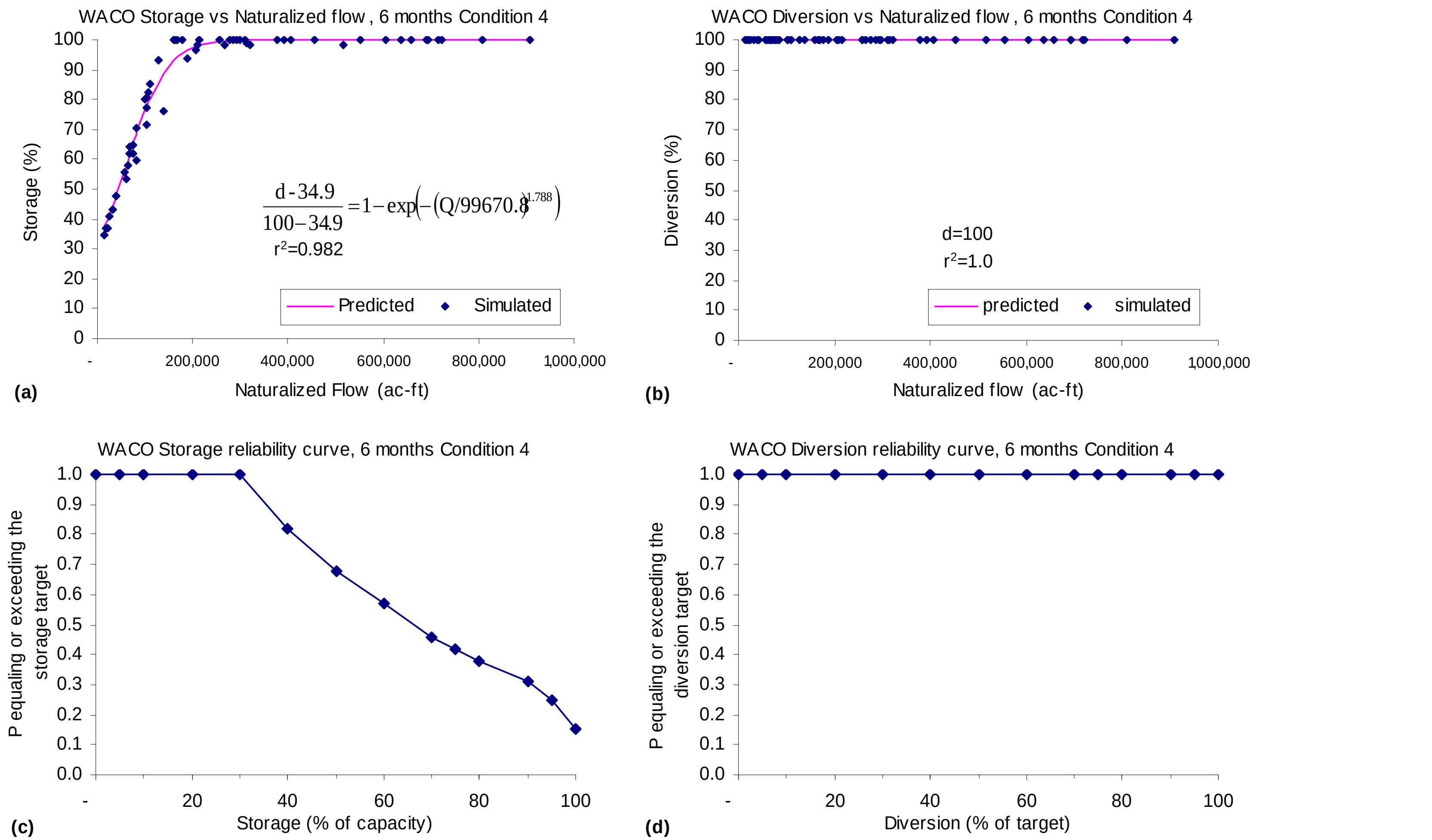


FIGURE A.9 Condition 4 simulation results for Lake Waco for 6 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

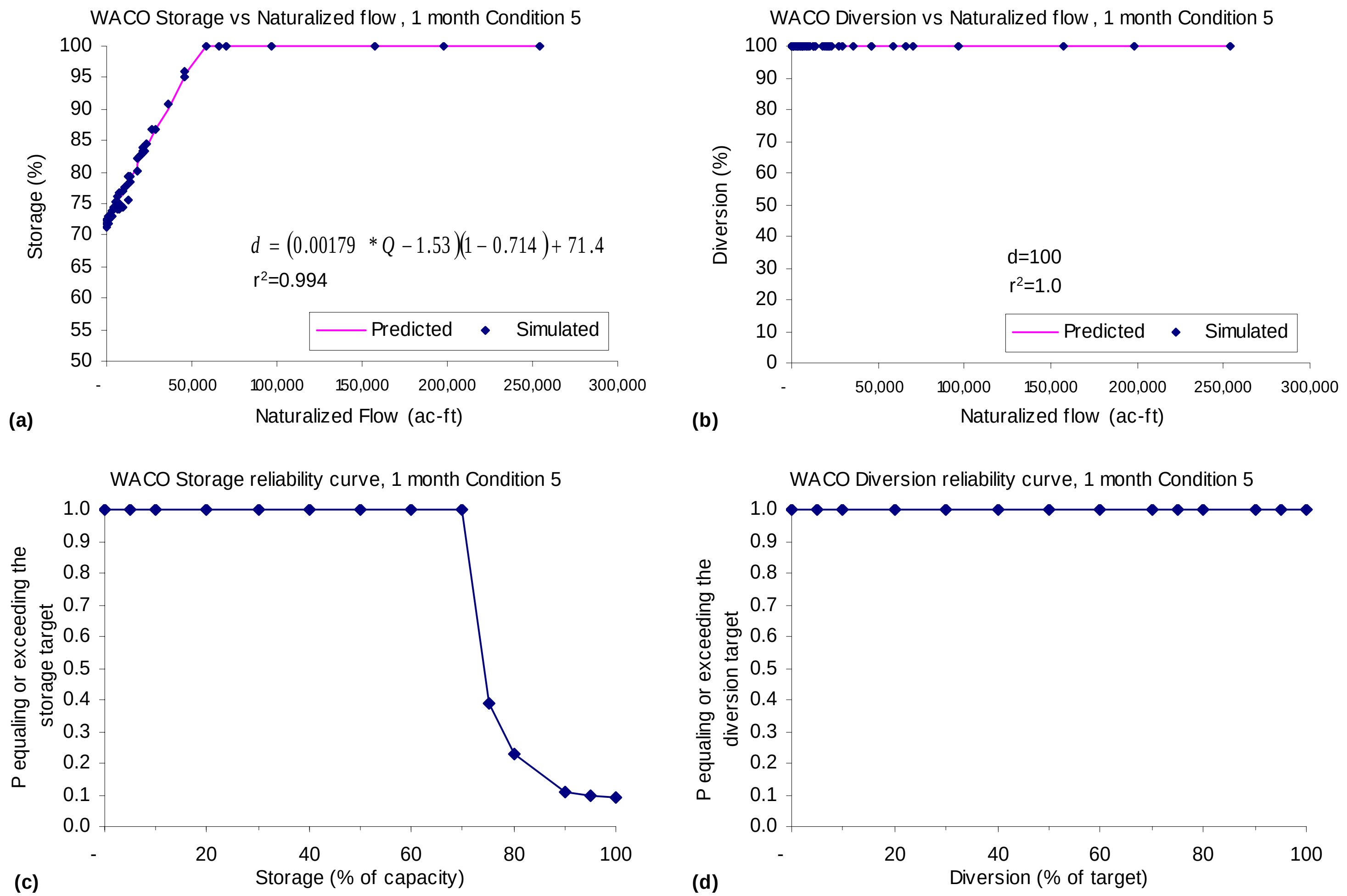


FIGURE A.10 Condition 5 simulation results for Lake Waco for 1 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

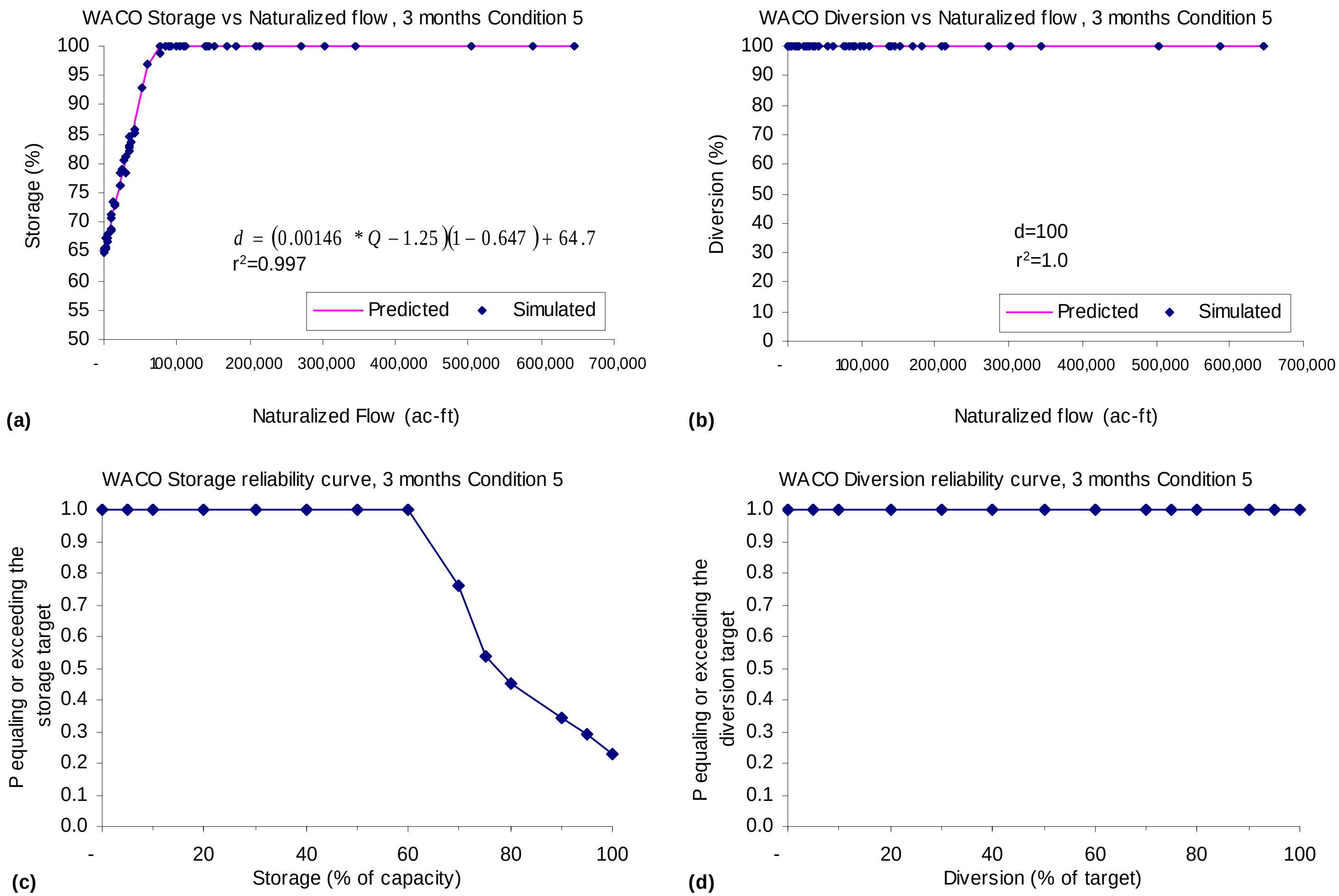


FIGURE A.11 Condition 5 simulation results for Lake Waco for 3 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

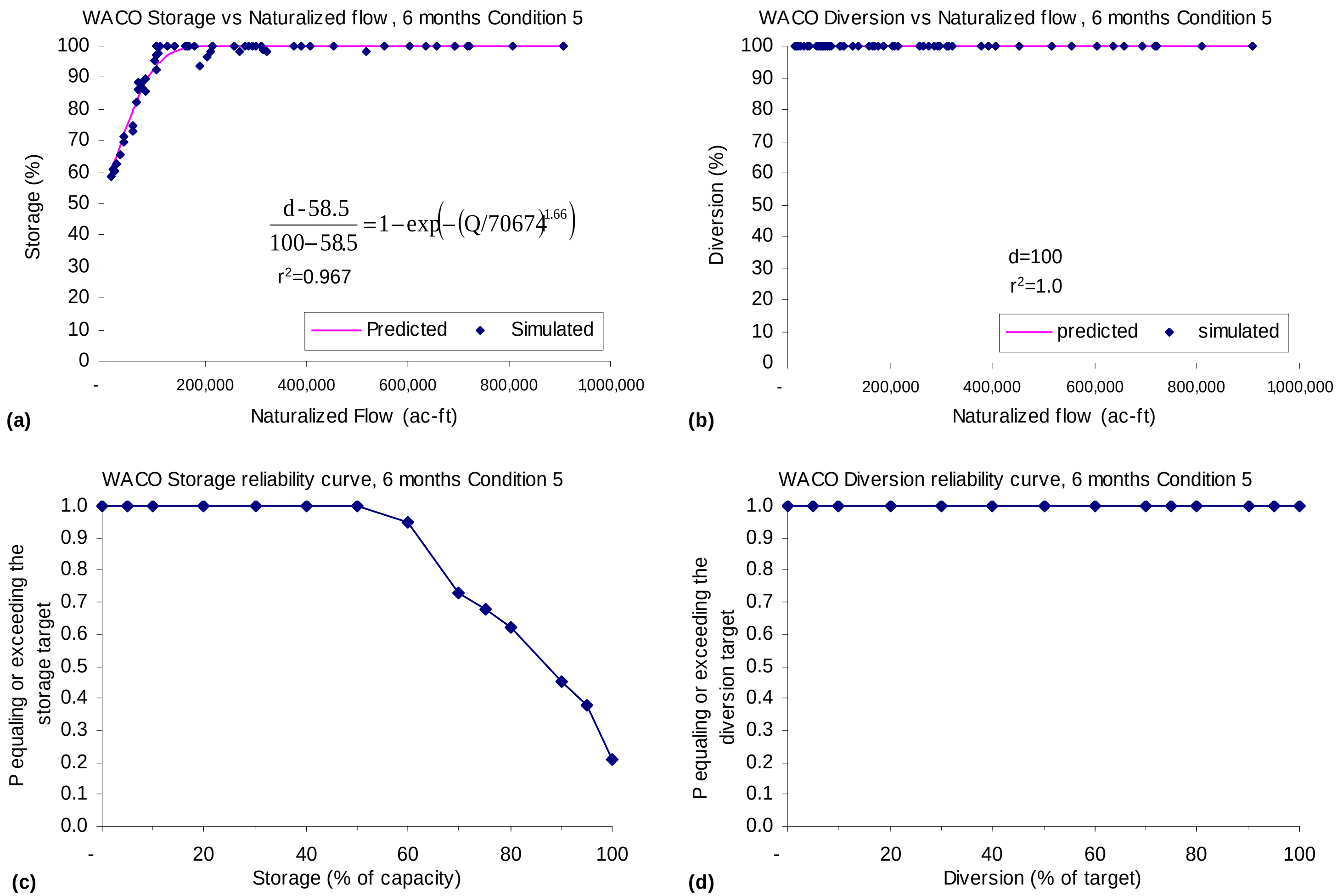


FIGURE A.12 Condition 5 simulation results for Lake Waco for 6 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

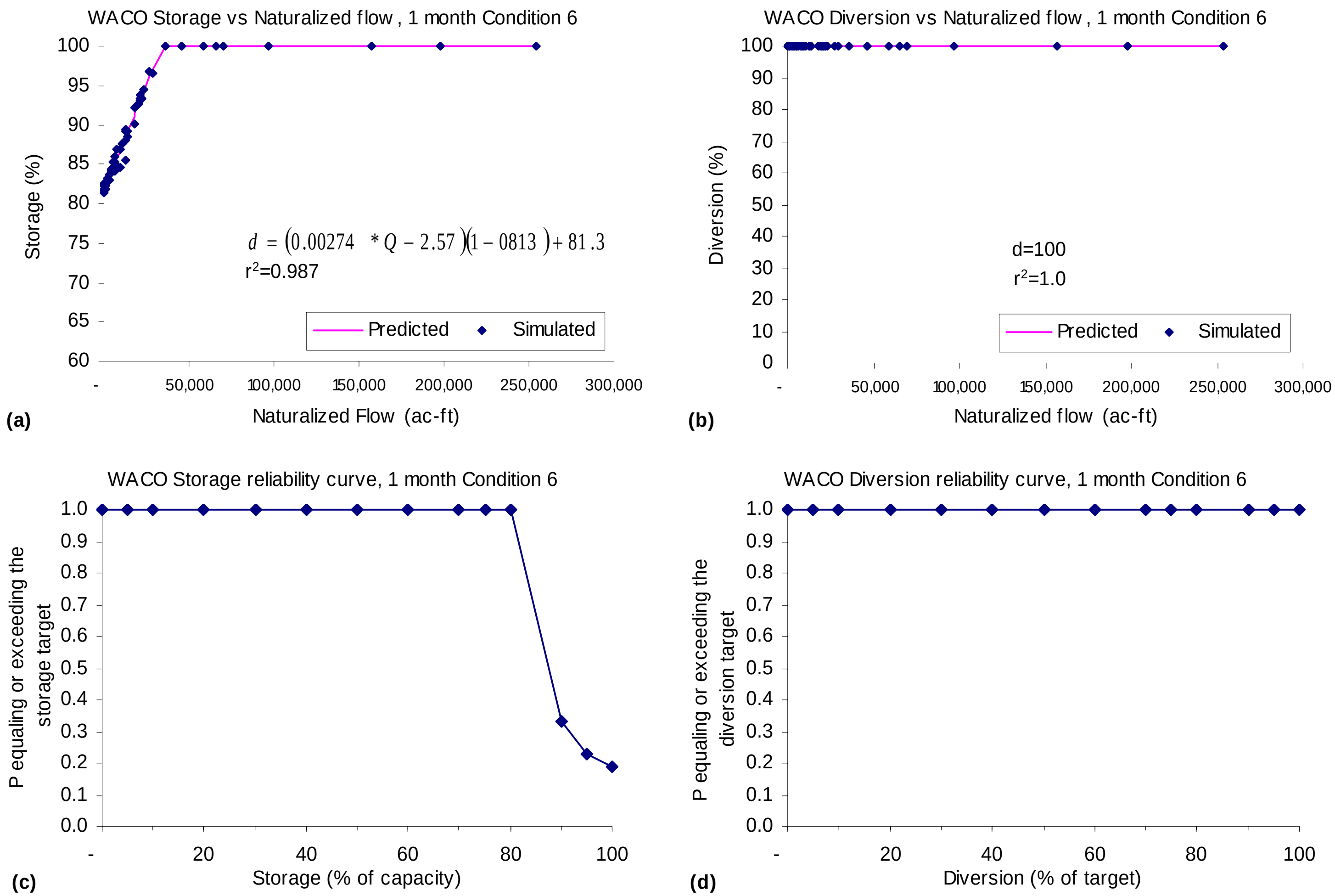


FIGURE A.13 Condition 6 simulation results for Lake Waco for 1 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

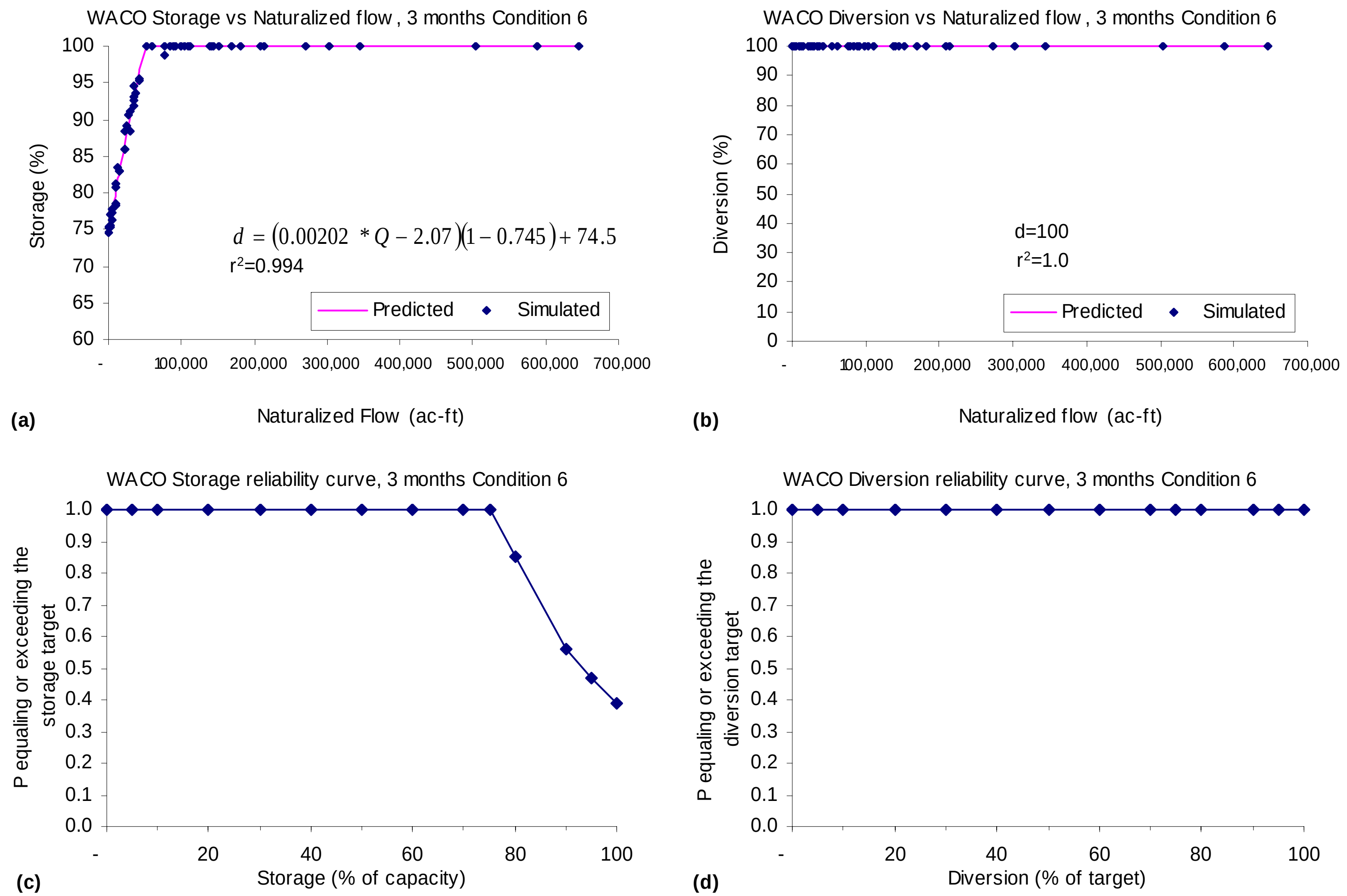


FIGURE A.14 Condition 6 simulation results for Lake Waco for 3 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

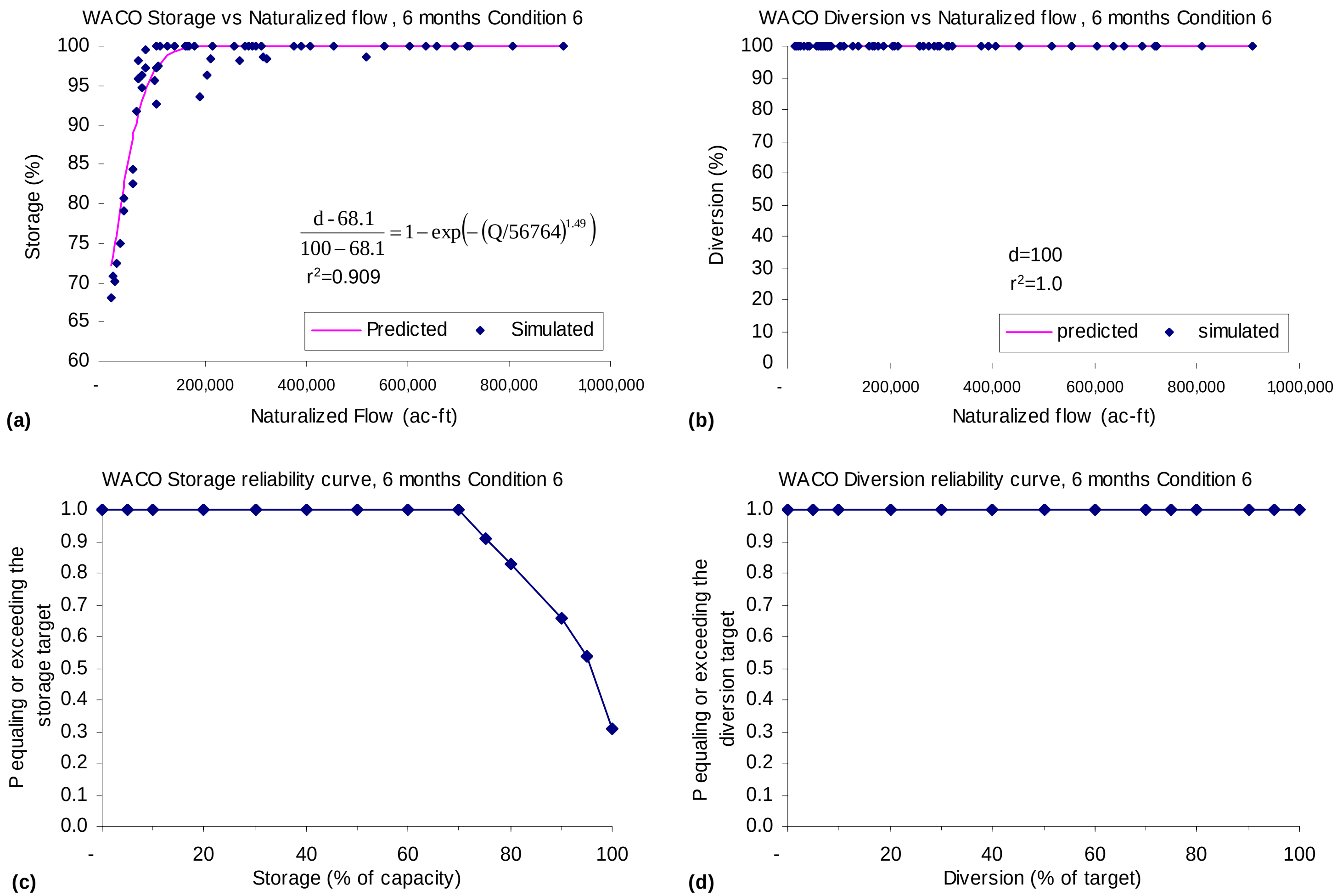


FIGURE A.15 Condition 6 simulation results for Lake Waco for 6 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

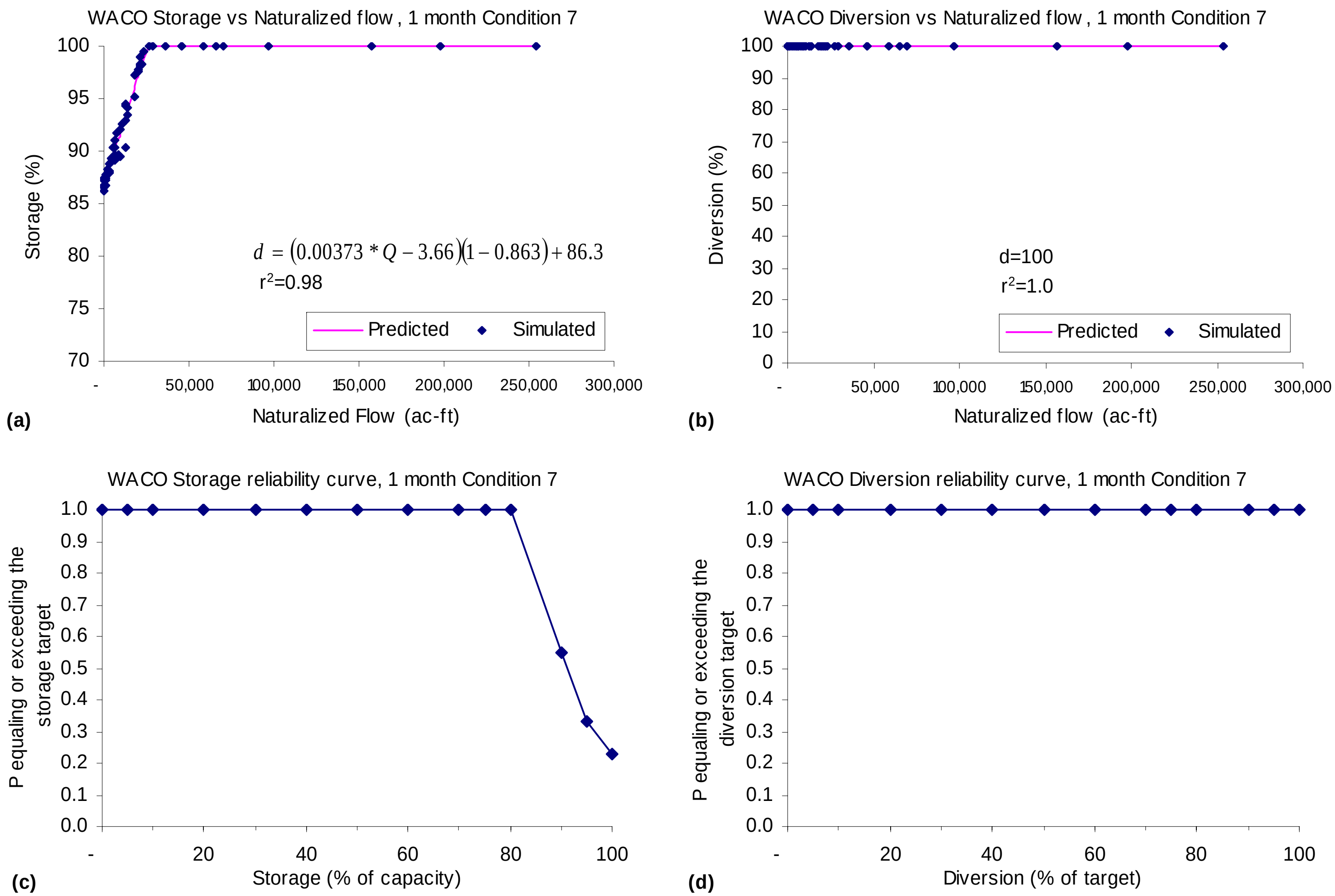


FIGURE A.16 Condition 7 simulation results for Lake Waco for 1 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

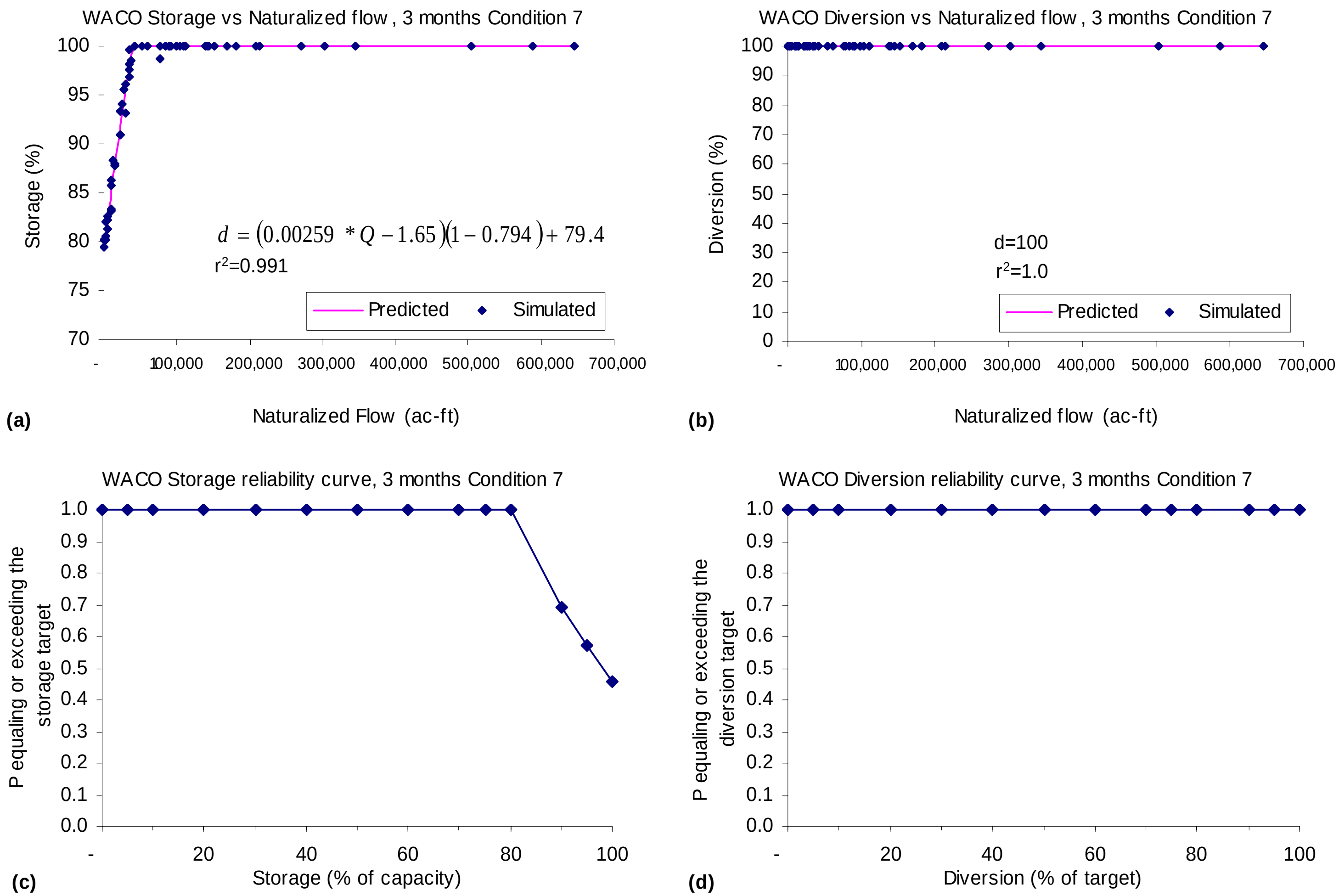


FIGURE A.17 Condition 7 simulation results for Lake Waco for 3 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

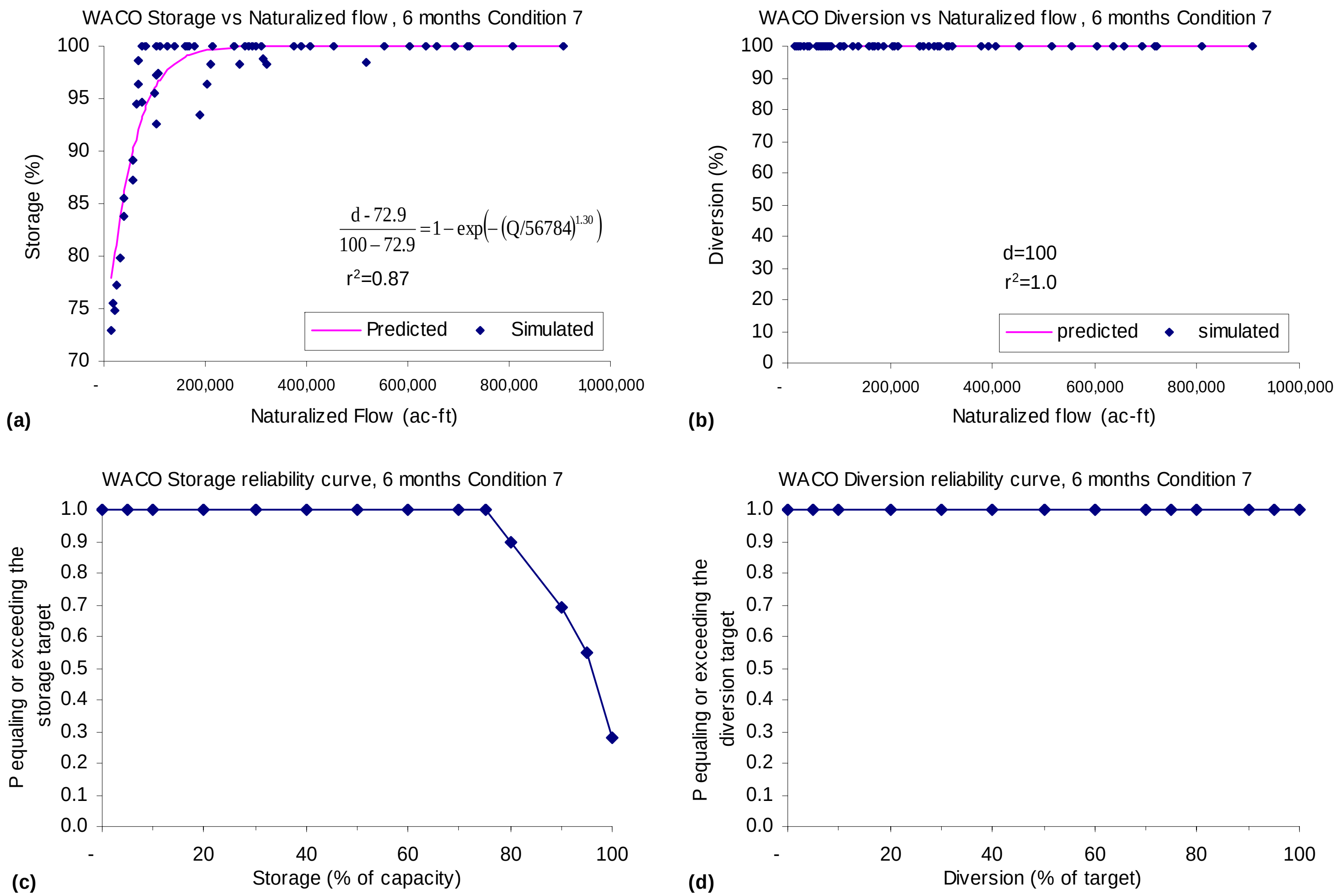


FIGURE A.18 Condition 7 simulation results for Lake Waco for 6 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

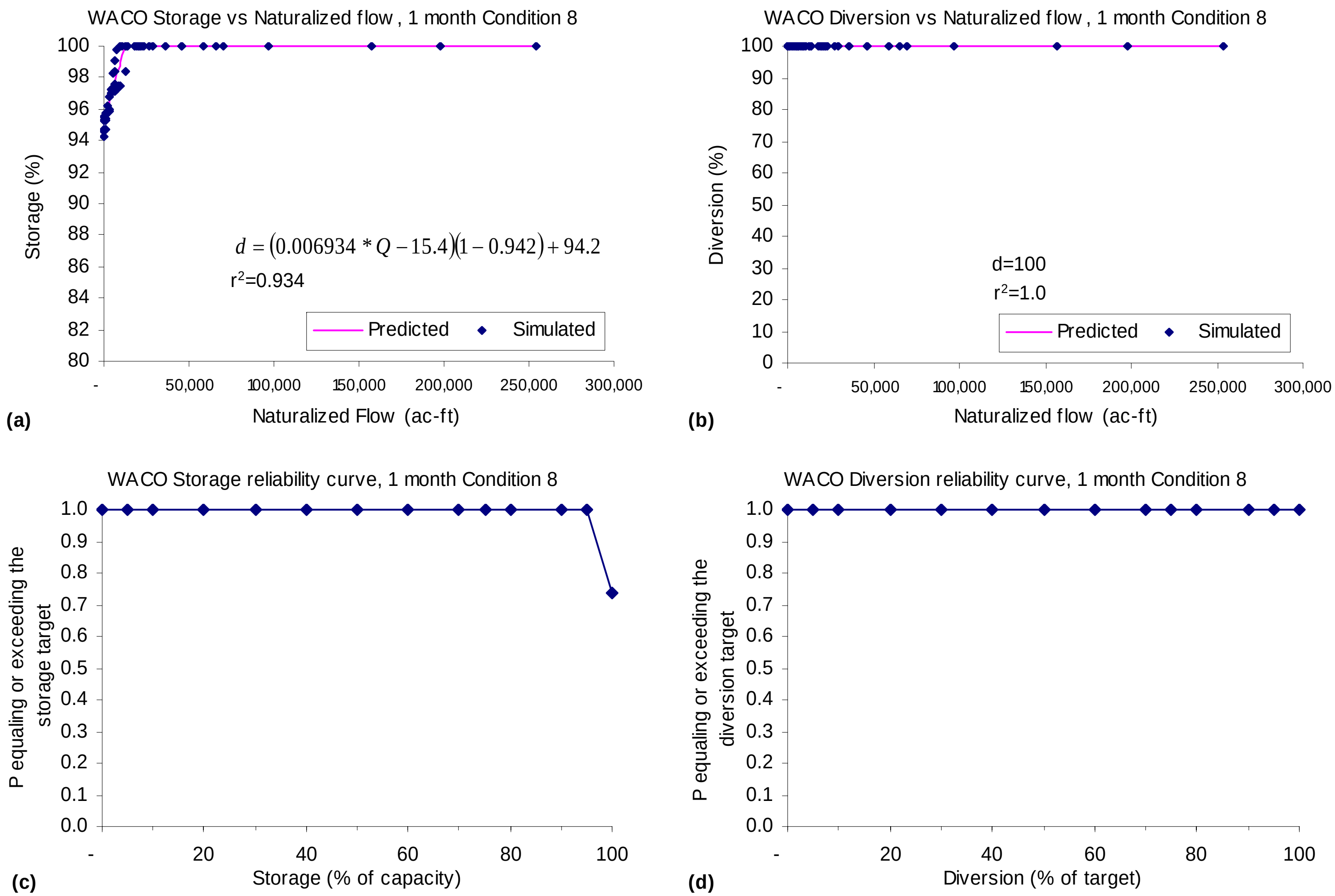


FIGURE A.19 Condition 8 simulation results for Lake Waco for 1 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

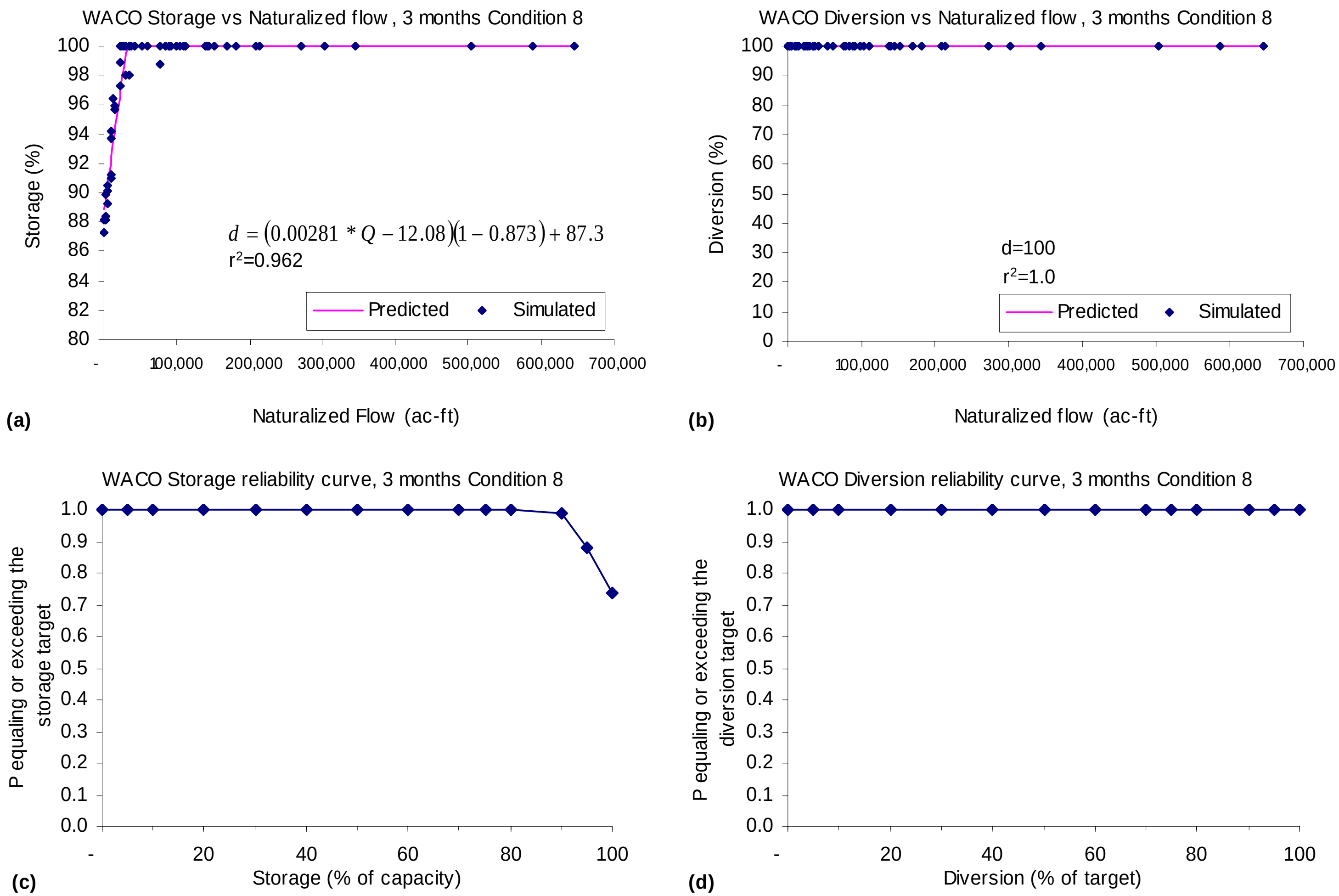


FIGURE A.20 Condition 8 simulation results for Lake Waco for 3 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

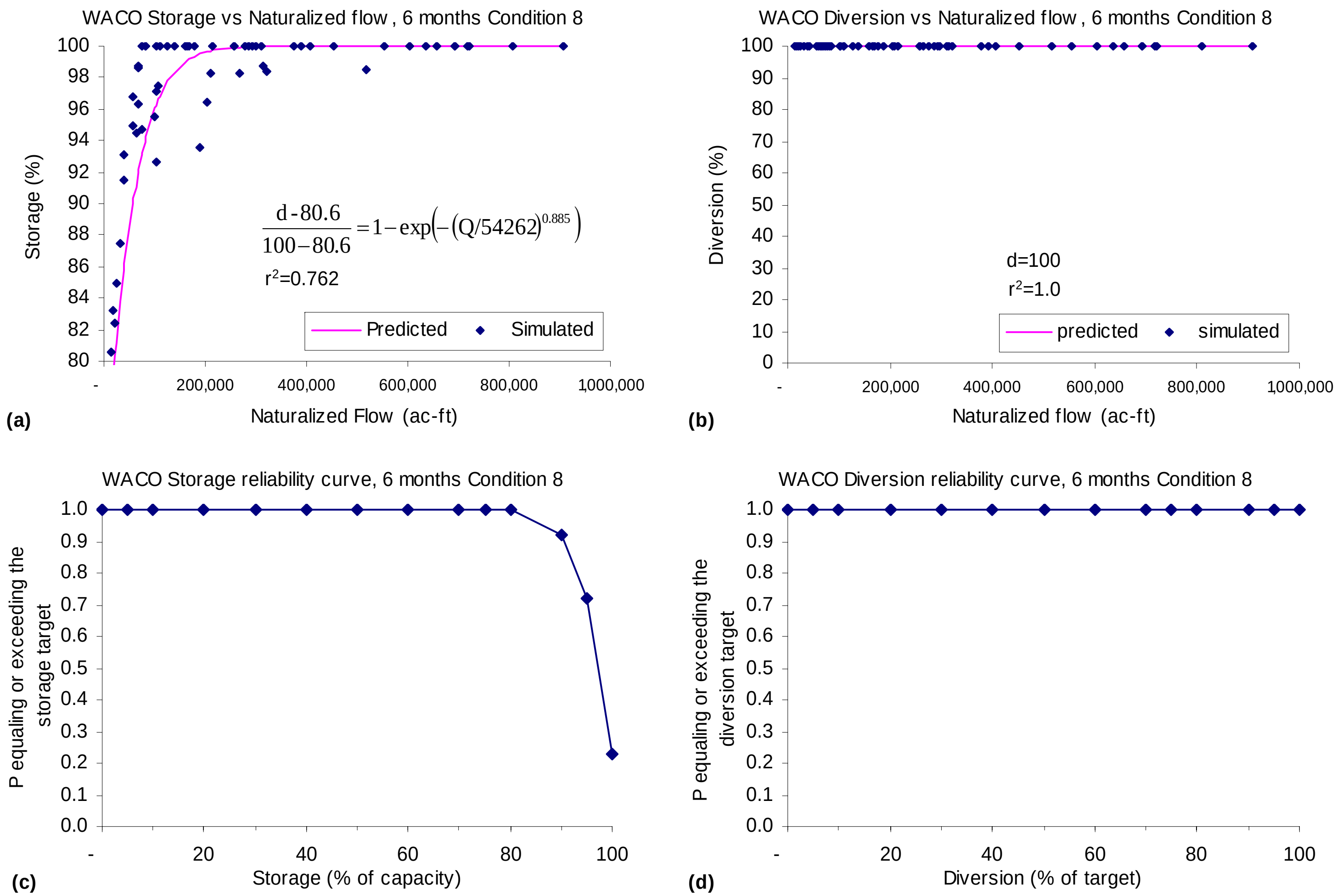


FIGURE A.21 Condition 8 simulation results for Lake Waco for 6 months; (a) Flow-Storage regression; (b) Flow-Diversion regression; (c) Storage reliability curve; (d) Diversion reliability curve

TABLE A.1 Storage reliabilities for Lake Waco, combination H

Period	Initial Storage	Expected Values for Drawdown (Ac-ft)	P-full Rel (%)	Storage Rel (%)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table											
					100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	172665	4.87	10.10	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.09	0.1	0.19
	10%	156448	4.87	18.50	0.05	0.05	0.06	0.07	0.07	0.07	0.08	0.09	0.09	0.1	0.19	0.46
	25%	129461	6.19	32.60	0.06	0.07	0.07	0.08	0.08	0.08	0.09	0.1	0.13	0.26	1	1
	50%	85037	6.27	55.70	0.06	0.08	0.09	0.09	0.1	0.1	0.19	0.44	1	1	1	1
	75%	41694	9.39	78.30	0.09	0.1	0.13	0.25	0.4	1	1	1	1	1	1	1
	85%	21881	18.75	88.60	0.19	0.23	0.33	1	1	1	1	1	1	1	1	1
	90%	14329	22.65	92.50	0.23	0.33	0.55	1	1	1	1	1	1	1	1	1
	98%	1437	73.52	99.30	0.74	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	152494	7.93	20.60	0.08	0.09	0.09	0.09	0.09	0.1	0.11	0.14	0.19	0.24	0.33	0.45
	10%	139290	8.60	27.50	0.09	0.09	0.09	0.1	0.1	0.11	0.14	0.19	0.24	0.32	0.43	0.58
	25%	113736	9.28	40.80	0.09	0.1	0.1	0.12	0.14	0.16	0.21	0.27	0.37	0.49	0.79	1
	50%	71683	10.13	62.70	0.1	0.16	0.18	0.23	0.27	0.32	0.43	0.57	1	1	1	1
	75%	33897	23.17	82.40	0.23	0.31	0.36	0.48	0.56	0.76	1	1	1	1	1	1
	85%	16755	38.66	91.30	0.39	0.46	0.55	0.86	1	1	1	1	1	1	1	1
	90%	11205	44.60	94.20	0.45	0.56	0.69	1	1	1	1	1	1	1	1	1
	98%	2621	73.59	98.60	0.74	0.87	0.99	1	1	1	1	1	1	1	1	1
6 months	0%	115607	9.07	39.80	0.09	0.18	0.2	0.24	0.25	0.28	0.32	0.36	0.4	0.46	0.53	0.68
	10%	109777	12.86	42.80	0.13	0.21	0.24	0.28	0.3	0.32	0.36	0.4	0.44	0.48	0.57	0.69
	25%	88950	11.39	53.70	0.11	0.22	0.25	0.32	0.35	0.37	0.42	0.47	0.55	0.65	0.76	1
	50%	58050	14.74	69.80	0.15	0.26	0.32	0.4	0.44	0.47	0.6	0.7	0.85	1	1	1
	75%	28908	20.04	84.90	0.2	0.39	0.46	0.64	0.7	0.77	0.96	1	1	1	1	1
	85%	15411	31.29	92.00	0.31	0.55	0.66	0.82	0.9	1	1	1	1	1	1	1
	90%	13118	28.07	93.20	0.28	0.55	0.69	0.89	1	1	1	1	1	1	1	1
	98%	6822	22.56	96.40	0.23	0.69	0.91	1	1	1	1	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE A.2 Diversion reliabilities for Lake Waco, combination H

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table: 100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	5137.5	1765.0	44.0	65.6	0.44	0.48	0.50	0.54	0.55	0.57	0.60	0.64	0.68	0.72	0.78	0.85
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	15504	4163.8	20.6	73.1	0.21	0.42	0.47	0.54	0.57	0.60	0.70	0.77	0.82	0.87	0.91	0.96
	10%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
6 months	0%	35505.2	7697.1	5.9	78.3	0.06	0.09	0.13	0.29	0.47	0.95	1	1	1	1	1	1
	10%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1

TABLE A.3 Storage reliabilities for Lake Waco, combination E

Period	Initial Storage	Expected Values for Drawdown (Ac-ft)	P-full Rel (%)	Storage Rel (%)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table											
					100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	172889	4.84	10.00	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.09	0.1	0.19
	10%	156690	4.85	18.40	0.05	0.05	0.06	0.07	0.07	0.07	0.08	0.09	0.09	0.1	0.19	0.45
	25%	129694	6.16	32.50	0.06	0.07	0.07	0.08	0.08	0.08	0.09	0.1	0.12	0.26	1	1
	50%	85251	6.24	55.60	0.06	0.08	0.09	0.09	0.09	0.1	0.19	0.43	1	1	1	1
	75%	41886	9.34	78.20	0.09	0.1	0.12	0.25	0.4	1	1	1	1	1	1	1
	85%	21597	19.13	88.80	0.19	0.24	0.35	1	1	1	1	1	1	1	1	1
	90%	14107	23.47	92.70	0.23	0.34	0.55	1	1	1	1	1	1	1	1	1
	98%	1390	73.07	99.30	0.73	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	152723	7.93	20.50	0.08	0.09	0.09	0.09	0.09	0.1	0.11	0.14	0.18	0.24	0.33	0.45
	10%	139506	8.60	27.40	0.09	0.09	0.09	0.1	0.1	0.11	0.14	0.18	0.23	0.32	0.43	0.59
	25%	113953	9.28	40.70	0.09	0.1	0.1	0.12	0.14	0.16	0.21	0.27	0.37	0.49	0.8	1
	50%	71921	10.12	62.60	0.1	0.16	0.18	0.23	0.27	0.31	0.43	0.57	1	1	1	1
	75%	34009	22.81	82.30	0.23	0.3	0.36	0.48	0.56	0.76	1	1	1	1	1	1
	85%	16735	40.03	91.30	0.4	0.47	0.54	0.85	1	1	1	1	1	1	1	1
	90%	11300	45.60	94.10	0.46	0.55	0.69	1	1	1	1	1	1	1	1	1
	98%	2581	73.56	98.70	0.74	0.87	0.99	1	1	1	1	1	1	1	1	1
6 months	0%	115362	9.21	39.90	0.09	0.18	0.21	0.24	0.25	0.28	0.32	0.36	0.4	0.46	0.53	0.68
	10%	109537	13.23	43.00	0.13	0.21	0.24	0.28	0.3	0.32	0.36	0.4	0.44	0.48	0.58	0.69
	25%	88682	11.67	53.80	0.12	0.22	0.25	0.32	0.35	0.37	0.42	0.47	0.55	0.66	0.77	0.98
	50%	58289	14.37	69.70	0.14	0.26	0.32	0.4	0.44	0.47	0.59	0.71	0.85	1	1	1
	75%	28780	20.28	85.00	0.2	0.39	0.46	0.64	0.71	0.78	0.94	1	1	1	1	1
	85%	15806	31.57	91.80	0.32	0.54	0.65	0.81	0.9	1	1	1	1	1	1	1
	90%	13361	28.77	93.00	0.29	0.54	0.68	0.89	1	1	1	1	1	1	1	1
	98%	6767	22.22	96.50	0.22	0.7	0.91	1	1	1	1	1	1	1	1	1

Tot Storage: 347062

TABLE A.4 Diversion reliabilities for Lake Waco, combination E

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table 100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	5137.5	1786.6	43.6	65.2	0.44	0.48	0.50	0.53	0.55	0.56	0.59	0.63	0.67	0.72	0.78	0.85
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	15504	4151.0	20.3	73.2	0.20	0.42	0.47	0.54	0.57	0.60	0.70	0.77	0.82	0.87	0.91	0.96
	10%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
6 months	0%	35505.2	7678.8	6.0	78.4	0.06	0.09	0.14	0.29	0.48	0.94	1	1	1	1	1	1
	10%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1

TABLE A.5 Storage reliabilities for Lake Waco, combination A

Period	Initial Storage	Expected Values for Drawdown (Ac-ft)	P-full Rel (%)	Storage Rel (%)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table: 100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	172944	4.78	10.00	0.05	0.05	0.05	0.06	0.06	0.07	0.07	0.08	0.09	0.09	0.10	0.19
	10%	156649	4.78	18.40	0.05	0.05	0.06	0.07	0.07	0.07	0.08	0.09	0.09	0.10	0.19	0.47
	25%	129640	6.12	32.50	0.06	0.06	0.07	0.08	0.08	0.08	0.09	0.10	0.13	0.25	1	1
	50%	85185	6.19	55.60	0.06	0.08	0.09	0.09	0.10	0.10	0.18	0.45	1	1	1	1
	75%	41822	9.35	78.20	0.09	0.10	0.12	0.24	0.41	1	1	1	1	1	1	1
	85%	24655	11.87	87.20	0.12	0.18	0.24	1	1	1	1	1	1	1	1	1
	90%	16530	17.27	91.40	0.17	0.24	0.41	1	1	1	1	1	1	1	1	1
	98%	2033	64.10	98.90	0.64	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	152432	7.92	20.60	0.08	0.09	0.09	0.09	0.09	0.10	0.11	0.14	0.19	0.24	0.32	0.45
	10%	139046	8.60	27.60	0.09	0.09	0.09	0.10	0.10	0.11	0.14	0.19	0.23	0.31	0.43	0.62
	25%	113495	9.30	40.90	0.09	0.10	0.10	0.12	0.14	0.16	0.21	0.27	0.36	0.51	0.80	1
	50%	71498	10.16	62.80	0.10	0.16	0.18	0.23	0.26	0.31	0.42	0.60	1	1	1	1
	75%	33638	22.86	82.50	0.23	0.30	0.35	0.49	0.59	0.76	1	1	1	1	1	1
	85%	20281	32.55	89.40	0.33	0.41	0.49	0.76	1	1	1	1	1	1	1	1
	90%	14246	39.02	92.60	0.39	0.49	0.59	1	1	1	1	1	1	1	1	1
	98%	3240	68.43	98.30	0.68	0.83	1	1	1	1	1	1	1	1	1	1
6 months	0%	113463	9.59	40.90	0.10	0.19	0.22	0.26	0.28	0.30	0.34	0.37	0.40	0.47	0.55	0.68
	10%	107724	14.11	43.90	0.14	0.23	0.25	0.30	0.32	0.34	0.37	0.40	0.44	0.49	0.58	0.69
	25%	87241	12.29	54.60	0.12	0.24	0.27	0.33	0.36	0.38	0.42	0.48	0.56	0.66	0.77	1
	50%	56869	16.15	70.40	0.16	0.29	0.34	0.40	0.45	0.49	0.60	0.71	0.85	1	1	1
	75%	28100	21.53	85.40	0.22	0.39	0.47	0.65	0.71	0.78	0.96	1	1	1	1	1
	85%	17878	23.09	90.70	0.23	0.47	0.61	0.79	0.88	1	1	1	1	1	1	1
	90%	15245	21.24	92.10	0.21	0.47	0.65	0.87	1	1	1	1	1	1	1	1
	98%	7307	20.78	96.20	0.21	0.68	0.88	1	1	1	1	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE A.6 Diversion reliabilities for Lake Waco, combination A

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Expected Values for Period Rel (%)	Expected Values for Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table											
						100	95	90	80	75	70	60	50	40	30	20	10
1 month	0%	5137.5	1815.1	40.8	64.7	0.41	0.46	0.49	0.52	0.54	0.55	0.58	0.63	0.67	0.72	0.78	0.85
	10%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
3 months	0%	15504.0	4274.6	20.3	72.4	0.20	0.38	0.45	0.53	0.56	0.59	0.69	0.77	0.82	0.87	0.92	0.96
	10%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
6 months	0%	35505.2	7737	6.2	78.2	0.06	0.09	0.14	0.28	0.46	0.96	1	1	1	1	1	1
	10%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	25%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	50%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	75%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	85%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	90%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1
	98%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1	1	1	1	1	1

TABLE A.7 Equally likely storage reliabilities for Lake Waco

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	20311.61	0.02	0.02	0.03	0.03	0.05	0.05	0.12	0.21	1
	10%	37633.25	0.03	0.03	0.03	0.03	0.05	0.07	0.17	0.69	1
	25%	65206.91	0.05	0.05	0.05	0.05	0.05	0.12	0.69	1	1
	50%	110019.3	0.05	0.05	0.07	0.07	0.12	0.67	1	1	1
	75%	153990.9	0.12	0.12	0.14	0.17	0.55	1	1	1	1
	85%	170649.2	0.17	0.17	0.21	0.36	1	1	1	1	1
	90%	178570.7	0.21	0.26	0.36	0.57	1	1	1	1	1
	98%	188807.2	0.48	0.59	0.93	1	1	1	1	1	1
3 months	0%	62485.54	0.10	0.12	0.14	0.14	0.17	0.24	0.47	0.55	1
	10%	75739.06	0.14	0.14	0.14	0.16	0.19	0.33	0.5	0.74	1
	25%	99545.11	0.17	0.17	0.17	0.19	0.24	0.47	0.74	1	1
	50%	136303.7	0.24	0.24	0.28	0.33	0.45	0.74	1	1	1
	75%	166870.1	0.45	0.47	0.48	0.5	0.72	1	1	1	1
	85%	176882.9	0.48	0.5	0.53	0.66	0.98	1	1	1	1
	90%	181698.9	0.52	0.57	0.66	0.74	1	1	1	1	1
	98%	187443.1	0.66	0.72	0.79	0.9	1	1	1	1	1
6 months	0%	118124.4	0.31	0.41	0.41	0.43	0.47	0.59	0.72	0.88	1
	10%	124437.6	0.31	0.41	0.43	0.45	0.52	0.6	0.83	0.91	1
	25%	137639.7	0.35	0.43	0.47	0.52	0.53	0.69	0.88	1	1
	50%	155050.5	0.43	0.53	0.55	0.59	0.64	0.85	1	1	1
	75%	174822.7	0.47	0.57	0.64	0.69	0.81	1	1	1	1
	85%	181528.1	0.5	0.6	0.76	0.81	0.91	1	1	1	1
	90%	184212.3	0.57	0.69	0.78	0.85	0.97	1	1	1	1
	98%	186727	0.57	0.69	0.79	0.91	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE A.8 Equally likely diversion reliabilities for Lake Waco

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for			Probability (0 to 1) of meeting or exceeding the % of volume diversion shown header of table						
			Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	100	98	95	90	75	50	0
1 month	0%	5137.5	1052.9	69.0	79.5	0.69	0.69	0.69	0.71	0.72	0.79	1.00
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504	2622.9	73.6	83.1	0.67	0.67	0.67	0.72	0.74	0.85	1.00
	10%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504	0.0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	3324.4	82.2	90.6	0.66	0.66	0.71	0.74	0.83	0.97	1
	10%	35505.2	47.4	99.4	99.9	0.983	0.983	0.983	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1

APPENDIX B

RESULTS FOR THE CONDITIONAL RELIABILITY MODEL USING THE SFF APPROACH

TABLE B.1 Storage reliabilities for Lake Waco, combination H

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	25.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14483.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1
	25%	44205.3	0.00	0.00	0.00	0.00	0.00	0.00	0.07	1.00	1
	50%	95669.4	0.00	0.00	0.00	0.00	0.01	0.28	1	1	1
	75%	152425.8	0.09	0.09	0.10	0.15	0.52	1	1	1	1
	85%	174242.1	0.27	0.27	0.32	0.49	1	1	1	1	1
	90%	182969.8	0.45	0.51	0.53	0.73	1	1	1	1	1
	98%	190290.8	0.73	0.78	0.93	1	1	1	1	1	1
3 months	0%	5531.1	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.07	1
	10%	19305.1	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.26	1
	25%	54176.0	0.02	0.02	0.02	0.03	0.03	0.07	0.43	1.00	1
	50%	115793.8	0.08	0.08	0.10	0.11	0.18	0.59	1	1	1
	75%	168766.6	0.44	0.46	0.50	0.53	0.74	1	1	1	1
	85%	181505.6	0.59	0.59	0.67	0.74	1	1	1	1	1
	90%	186278.7	0.69	0.71	0.78	0.86	1	1	1	1	1
	98%	190394.4	0.84	0.88	0.94	1	1	1	1	1	1
6 months	0%	64151.9	0.04	0.07	0.07	0.11	0.17	0.27	0.47	0.64	1
	10%	79544.3	0.07	0.11	0.17	0.22	0.26	0.34	0.58	0.76	1
	25%	104706.2	0.14	0.23	0.26	0.27	0.31	0.52	0.71	1	1
	50%	142311.5	0.35	0.42	0.42	0.49	0.52	0.74	1	1	1
	75%	171316.4	0.35	0.49	0.59	0.64	0.77	1	1	1	1
	85%	180888.6	0.49	0.59	0.76	0.80	0.92	1	1	1	1
	90%	184321.6	0.60	0.72	0.79	0.84	0.96	1	1	1	1
	98%	187400.1	0.66	0.72	0.81	0.93	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE B.2 Diversion reliabilities at Lake Waco, for combination H

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table: 100	98	95	90	75	50	0
1 month	0%	5137.5	4641.3	0.1	9.7	0.00	0.00	0.00	0.01	0.01	0.03	1.00
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	8395.2	23.1	45.9	0.16	0.16	0.16	0.20	0.20	0.42	1.00
	10%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	6135.6	67.6	82.7	0.43	0.43	0.45	0.58	0.67	0.90	1
	10%	35505.2	211.5	97.4	99.4	0.92	0.92	0.92	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1

TABLE B.3 Storage reliabilities for Lake Waco, combination E

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14508.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	1
	25%	44023.0	0.00	0.00	0.00	0.00	0.00	0.00	0.08	1	1
	50%	95701.2	0.00	0.00	0.00	0.00	0.01	0.26	1	1	1
	75%	151859.6	0.09	0.09	0.11	0.16	0.48	1	1	1	1
	85%	173731.4	0.25	0.25	0.32	0	1	1	1	1	1
	90%	182575.4	0.42	0.48	0.53	1	1	1	1	1	1
	98%	190212.9	0.73	1	1	1	1	1	1	1	1
3 months	0%	6554.7	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.07	1
	10%	20178.5	0.01	0.01	0.01	0.01	0.02	0.03	0.07	0.29	1
	25%	54975.5	0.03	0.03	0.03	0.03	0.03	0.08	0.44	1	1
	50%	116226.3	0.08	0.08	0.10	0.11	0.21	0.58	1	1	1
	75%	168497.1	0.44	0.46	0.50	0.53	0.73	1	1	1	1
	85%	180917.0	0.57	0.58	0.62	0.73	1	1	1	1	1
	90%	185864.6	0.66	0.71	0.75	0.85	1	1	1	1	1
	98%	190352.2	0.84	0.88	0.93	0.99	1	1	1	1	1
6 months	0%	67321.8	0.04	0.06	0.06	0.13	0.22	0.27	0.48	0.65	1
	10%	80471.1	0.06	0.13	0.17	0.22	0.26	0.35	0.59	0.77	1
	25%	105434.1	0.15	0.23	0.26	0.27	0.32	0.52	0.71	1	1
	50%	142835.5	0.36	0.42	0.42	0.49	0.53	0.75	1	1	1
	75%	171300.6	0.36	0.52	0.59	0.64	0.77	1	1	1	1
	85%	180440.8	0.46	0.57	0.74	0.79	0.92	1	1	1	1
	90%	183908.0	0.55	0.68	0.78	0.84	0.97	1	1	1	1
	98%	187295.2	0.65	0.72	0.81	0.93	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE B.4 Diversion reliabilities for Lake Waco, combination E

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table 100	98	95	90	75	50	0
1 month	0%	5137.5	1052.9	69.0	79.5	0.69	0.69	0.69	0.71	0.72	0.79	1.00
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	2622.9	73.6	83.1	0.67	0.67	0.67	0.72	0.74	0.85	1.00
	10%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	3324.4	82.2	90.6	0.66	0.66	0.71	0.74	0.83	0.97	1
	10%	35505.2	999.7	87.9	97.2	0.64	0.64	0.64	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1

TABLE B.5 Storage reliabilities for Lake Waco, combination A

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	83.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14722.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1
	25%	44245.41	0.00	0.00	0.00	0.00	0.00	0.00	0.07	1.00	1
	50%	96013.4	0.00	0.00	0.00	0.00	0.01	0.34	1	1	1
	75%	152880.5	0.08	0.08	0.10	0.17	0.52	1	1	1	1
	85%	174809.2	0.30	0.30	0.39	0.50	1	1	1	1	1
	90%	182598	0.46	0.50	0.53	0.72	1	1	1	1	1
	98%	190185.7	0.72	0.77	0.93	1	1	1	1	1	1
3 months	0%	11186.88	0.01	0.02	0.02	0.02	0.02	0.03	0.04	0.11	1
	10%	26012.11	0.02	0.02	0.02	0.03	0.03	0.03	0.11	0.40	1
	25%	60888.11	0.03	0.03	0.03	0.03	0.04	0.11	0.48	1	1
	50%	121357.2	0.11	0.11	0.13	0.17	0.26	0.62	1	1	1
	75%	169984.6	0.46	0.47	0.52	0.55	0.78	1	1	1	1
	85%	181479	0.59	0.62	0.65	0.74	1	1	1	1	1
	90%	185919.5	0.66	0.69	0.77	0.85	1	1	1	1	1
	98%	190306.6	0.83	0.87	0.93	0.99	1	1	1	1	1
6 months	0%	77308.32	0.09	0.18	0.18	0.20	0.25	0.32	0.55	0.69	1
	10%	88664.84	0.12	0.19	0.23	0.26	0.27	0.46	0.62	0.81	1
	25%	111099.4	0.16	0.26	0.27	0.28	0.34	0.56	0.76	1	1
	50%	147159.8	0.33	0.41	0.45	0.54	0.57	0.77	1	1	1
	75%	171602.7	0.36	0.50	0.60	0.65	0.76	1	1	1	1
	85%	181058.1	0.50	0.61	0.76	0.79	0.92	1	1	1	1
	90%	184106.4	0.61	0.68	0.77	0.84	0.97	1	1	1	1
	98%	187098.5	0.60	0.70	0.80	0.93	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE B.6 Diversion reliabilities for Lake Waco, combination A

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown header of table 100	98	95	90	75	50	0
1 month	0%	5137.5	4602.7	0.3	10.4	0.00	0.00	0.00	0.00	0.01	0.03	1.00
	10%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	6913.24	35.7	55.4	0.27	0.27	0.27	0.31	0.32	0.54	1.00
	10%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	5456.18	71.7	84.6	0.48	0.48	0.50	0.63	0.70	0.91	1
	10%	35505.2	198.47	97.6	99.4	0.93	0.93	0.93	1	1	1	1
	25%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1

TABLE B.7 Storage reliabilities for Lake Waco, lognormal distribution, combination F

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	25.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14483.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1
	25%	44205.3	0.00	0.00	0.00	0.00	0.00	0.00	0.07	1.00	1
	50%	95669.4	0.00	0.00	0.00	0.00	0.01	0.28	1	1	1
	75%	152425.8	0.09	0.09	0.10	0.15	0.52	1	1	1	1
	85%	174242.1	0.27	0.27	0.32	0.49	1	1	1	1	1
	90%	182969.8	0.45	0.51	0.53	0.73	1	1	1	1	1
	98%	190290.8	0.73	0.78	0.93	1	1	1	1	1	1
3 months	0%	5531.1	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.07	1
	10%	19305.1	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.26	1
	25%	54176.0	0.02	0.02	0.02	0.03	0.03	0.07	0.43	1.00	1
	50%	115793.8	0.08	0.08	0.10	0.11	0.18	0.59	1	1	1
	75%	168766.6	0.44	0.46	0.50	0.53	0.74	1	1	1	1
	85%	181505.6	0.59	0.59	0.67	0.74	1	1	1	1	1
	90%	186278.7	0.69	0.71	0.78	0.86	1	1	1	1	1
	98%	190394.4	0.84	0.88	0.94	1	1	1	1	1	1
6 months	0%	64151.9	0.04	0.07	0.07	0.11	0.17	0.27	0.47	0.64	1
	10%	79544.3	0.07	0.11	0.17	0.22	0.26	0.34	0.58	0.76	1
	25%	104706.2	0.14	0.23	0.26	0.27	0.31	0.52	0.71	1	1
	50%	142311.5	0.35	0.42	0.42	0.49	0.52	0.74	1	1	1
	75%	171316.4	0.35	0.49	0.59	0.64	0.77	1	1	1	1
	85%	180888.6	0.49	0.59	0.76	0.80	0.92	1	1	1	1
	90%	184321.6	0.60	0.72	0.79	0.84	0.96	1	1	1	1
	98%	187400.1	0.66	0.72	0.81	0.93	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE B.8 Diversion reliabilities at Lake Waco, lognormal distribution, for combination F

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Expected Values for Period Rel (%)	Expected Values for Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table: 100	98	95	90	75	50	0
1 month	0%	5137.5	4641.3	0.1	9.7	0.00	0.00	0.00	0.01	0.01	0.03	1.00
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	8395.2	23.1	45.9	0.16	0.16	0.16	0.20	0.20	0.42	1.00
	10%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	6135.6	67.6	82.7	0.43	0.43	0.45	0.58	0.67	0.90	1
	10%	35505.2	211.5	97.4	99.4	0.92	0.92	0.92	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1

TABLE B.9Storage reliabilities for Lake Waco, lognormal distribution, combination H

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	25.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14483.6	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1
	25%	44205.3	0.00	0.00	0.00	0.00	0.00	0.00	0.07	1.00	1
	50%	95669.4	0.00	0.00	0.00	0.00	0.01	0.28	1	1	1
	75%	152425.8	0.09	0.09	0.10	0.15	0.52	1	1	1	1
	85%	174242.1	0.27	0.27	0.32	0.49	1	1	1	1	1
	90%	182969.8	0.45	0.51	0.53	0.73	1	1	1	1	1
	98%	190290.8	0.73	0.78	0.93	1	1	1	1	1	1
3 months	0%	5531.1	0.00	0.00	0.00	0.00	0.00	0.01	0.03	0.07	1
	10%	19305.1	0.00	0.00	0.00	0.01	0.01	0.03	0.07	0.26	1
	25%	54176.0	0.02	0.02	0.02	0.03	0.03	0.07	0.43	1.00	1
	50%	115793.8	0.08	0.08	0.10	0.11	0.18	0.59	1	1	1
	75%	168766.6	0.44	0.46	0.50	0.53	0.74	1	1	1	1
	85%	181505.6	0.59	0.59	0.67	0.74	1	1	1	1	1
	90%	186278.7	0.69	0.71	0.78	0.86	1	1	1	1	1
	98%	190394.4	0.84	0.88	0.94	1	1	1	1	1	1
6 months	0%	64151.9	0.04	0.07	0.07	0.11	0.17	0.27	0.47	0.64	1
	10%	79544.3	0.07	0.11	0.17	0.22	0.26	0.34	0.58	0.76	1
	25%	104706.2	0.14	0.23	0.26	0.27	0.31	0.52	0.71	1	1
	50%	142311.5	0.35	0.42	0.42	0.49	0.52	0.74	1	1	1
	75%	171316.4	0.35	0.49	0.59	0.64	0.77	1	1	1	1
	85%	180888.6	0.49	0.59	0.76	0.80	0.92	1	1	1	1
	90%	184321.6	0.60	0.72	0.79	0.84	0.96	1	1	1	1
	98%	187400.1	0.66	0.72	0.81	0.93	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE B.10 Diversion reliabilities at Lake Waco, lognormal distribution, for combination H

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table: 100	98	95	90	75	50	0
1 month	0%	5137.5	4641.3	0.1	9.7	0.00	0.00	0.00	0.01	0.01	0.03	1.00
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	8395.2	23.1	45.9	0.16	0.16	0.16	0.20	0.20	0.42	1.00
	10%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	6135.6	67.6	82.7	0.43	0.43	0.45	0.58	0.67	0.90	1
	10%	35505.2	211.5	97.4	99.4	0.92	0.92	0.92	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1

TABLE B.11 Storage reliabilities for Lake Waco, lognormal distribution, combination E

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14508.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	1
	25%	44023.0	0.00	0.00	0.00	0.00	0.00	0.00	0.08	1	1
	50%	95701.2	0.00	0.00	0.00	0.00	0.01	0.26	1	1	1
	75%	151859.6	0.09	0.09	0.11	0.16	0.48	1	1	1	1
	85%	173731.4	0.25	0.25	0.32	0	1	1	1	1	1
	90%	182575.4	0.42	0.48	0.53	1	1	1	1	1	1
	98%	190212.9	0.73	1	1	1	1	1	1	1	1
3 months	0%	6554.7	0.00	0.00	0.00	0.00	0.01	0.01	0.03	0.07	1
	10%	20178.5	0.01	0.01	0.01	0.01	0.02	0.03	0.07	0.29	1
	25%	54975.5	0.03	0.03	0.03	0.03	0.03	0.08	0.44	1	1
	50%	116226.3	0.08	0.08	0.10	0.11	0.21	0.58	1	1	1
	75%	168497.1	0.44	0.46	0.50	0.53	0.73	1	1	1	1
	85%	180917.0	0.57	0.58	0.62	0.73	1	1	1	1	1
	90%	185864.6	0.66	0.71	0.75	0.85	1	1	1	1	1
	98%	190352.2	0.84	0.88	0.93	0.99	1	1	1	1	1
6 months	0%	67321.8	0.04	0.06	0.06	0.13	0.22	0.27	0.48	0.65	1
	10%	80471.1	0.06	0.13	0.17	0.22	0.26	0.35	0.59	0.77	1
	25%	105434.1	0.15	0.23	0.26	0.27	0.32	0.52	0.71	1	1
	50%	142835.5	0.36	0.42	0.42	0.49	0.53	0.75	1	1	1
	75%	171300.6	0.36	0.52	0.59	0.64	0.77	1	1	1	1
	85%	180440.8	0.46	0.57	0.74	0.79	0.92	1	1	1	1
	90%	183908.0	0.55	0.68	0.78	0.84	0.97	1	1	1	1
	98%	187295.2	0.65	0.72	0.81	0.93	1	1	1	1	1

Total capacity: 192062 ac-ft

TABLE B.12 Diversion reliabilities for Lake Waco, lognormal distribution, combination E

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for			Probability (0 to 1) of meeting or exceeding the % of volume diversion shown in header of table						
			Shortage (Ac-ft)	Period Rel (%)	Volume Rel (%)	100	98	95	90	75	50	0
1 month	0%	5137.5	1052.9	69.0	79.5	0.69	0.69	0.69	0.71	0.72	0.79	1.00
	10%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0.0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	2622.9	73.6	83.1	0.67	0.67	0.67	0.72	0.74	0.85	1.00
	10%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0.0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	3324.4	82.2	90.6	0.66	0.66	0.71	0.74	0.83	0.97	1
	10%	35505.2	999.7	87.9	97.2	0.64	0.64	0.64	1	1	1	1
	25%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0.0	100.0	100.0	1	1	1	1	1	1	1

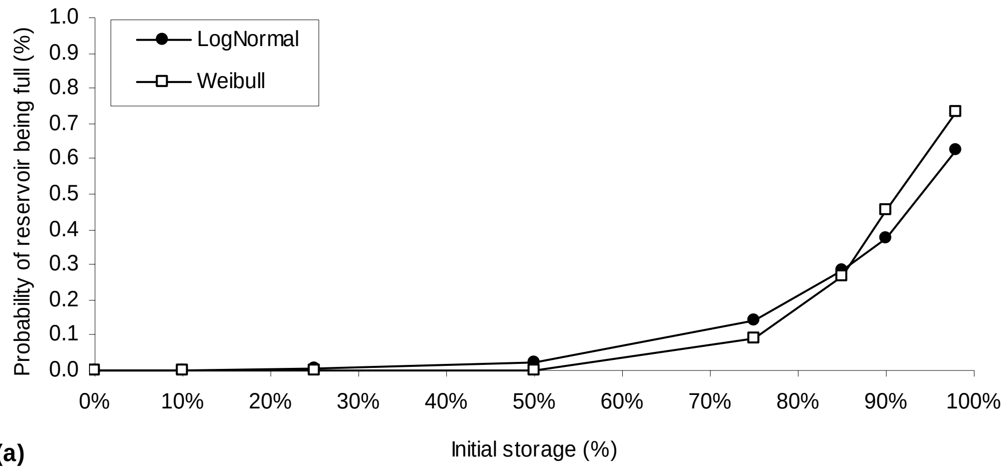
TABLE B.13 Storage reliabilities for Lake Waco, lognormal distribution, combination A

Period	Initial Storage	Mean Storage (Ac-ft)	Probability (0 to 1) of meeting or exceeding the % of storage capacity shown in header of table								
			100	98	95	90	75	50	25	10	0
1 month	0%	83.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1
	10%	14722.8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	1
	25%	44245.41	0.00	0.00	0.00	0.00	0.00	0.00	0.07	1.00	1
	50%	96013.4	0.00	0.00	0.00	0.00	0.01	0.34	1	1	1
	75%	152880.5	0.08	0.08	0.10	0.17	0.52	1	1	1	1
	85%	174809.2	0.30	0.30	0.39	0.50	1	1	1	1	1
	90%	182598	0.46	0.50	0.53	0.72	1	1	1	1	1
	98%	190185.7	0.72	0.77	0.93	1	1	1	1	1	1
3 months	0%	11186.88	0.01	0.02	0.02	0.02	0.02	0.03	0.04	0.11	1
	10%	26012.11	0.02	0.02	0.02	0.03	0.03	0.03	0.11	0.40	1
	25%	60888.11	0.03	0.03	0.03	0.03	0.04	0.11	0.48	1	1
	50%	121357.2	0.11	0.11	0.13	0.17	0.26	0.62	1	1	1
	75%	169984.6	0.46	0.47	0.52	0.55	0.78	1	1	1	1
	85%	181479	0.59	0.62	0.65	0.74	1	1	1	1	1
	90%	185919.5	0.66	0.69	0.77	0.85	1	1	1	1	1
	98%	190306.6	0.83	0.87	0.93	0.99	1	1	1	1	1
6 months	0%	77308.32	0.09	0.18	0.18	0.20	0.25	0.32	0.55	0.69	1
	10%	88664.84	0.12	0.19	0.23	0.26	0.27	0.46	0.62	0.81	1
	25%	111099.4	0.16	0.26	0.27	0.28	0.34	0.56	0.76	1	1
	50%	147159.8	0.33	0.41	0.45	0.54	0.57	0.77	1	1	1
	75%	171602.7	0.36	0.50	0.60	0.65	0.76	1	1	1	1
	85%	181058.1	0.50	0.61	0.76	0.79	0.92	1	1	1	1
	90%	184106.4	0.61	0.68	0.77	0.84	0.97	1	1	1	1
	98%	187098.5	0.60	0.70	0.80	0.93	1	1	1	1	1

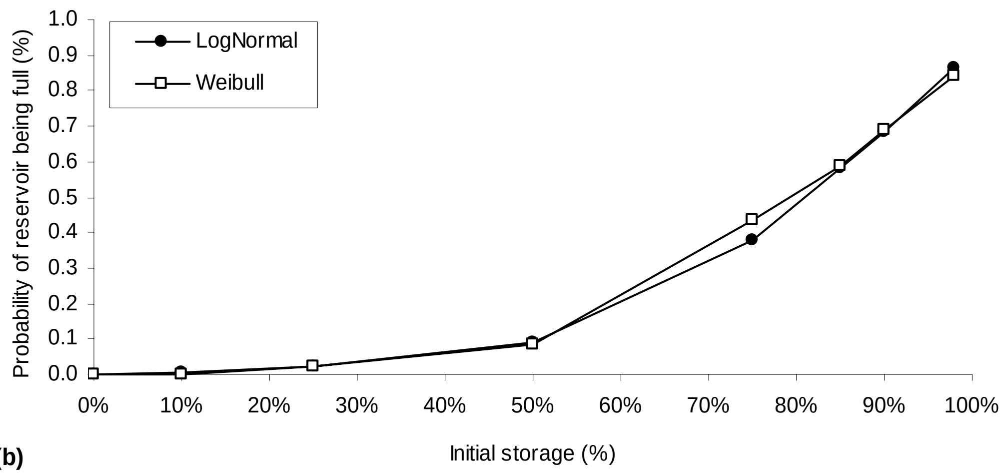
Total capacity: 192062 ac-ft

TABLE B.14 Diversion reliabilities for Lake Waco, lognormal distribution, combination A

Period	Initial Storage	Cumm Target (Ac-ft)	Expected Values for Shortage (Ac-ft)	Expected Values for Period Rel (%)	Expected Values for Volume Rel (%)	Probability (0 to 1) of meeting or exceeding the % of volume diversion shown header of table: 100	98	95	90	75	50	0
1 month	0%	5137.5	4602.7	0.3	10.4	0.00	0.00	0.00	0.00	0.01	0.03	1.00
	10%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	25%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	50%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	75%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	85%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	90%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
	98%	5137.5	0	100.0	100.0	1	1	1	1	1	1	1
3 months	0%	15504.0	6913.24	35.7	55.4	0.27	0.27	0.27	0.31	0.32	0.54	1.00
	10%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	25%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	50%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	75%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	85%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	90%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
	98%	15504.0	0	100.0	100.0	1	1	1	1	1	1	1
6 months	0%	35505.2	5456.18	71.7	84.6	0.48	0.48	0.50	0.63	0.70	0.91	1
	10%	35505.2	198.47	97.6	99.4	0.93	0.93	0.93	1	1	1	1
	25%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	50%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	75%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	85%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	90%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1
	98%	35505.2	0	100.0	100.0	1	1	1	1	1	1	1



(a)



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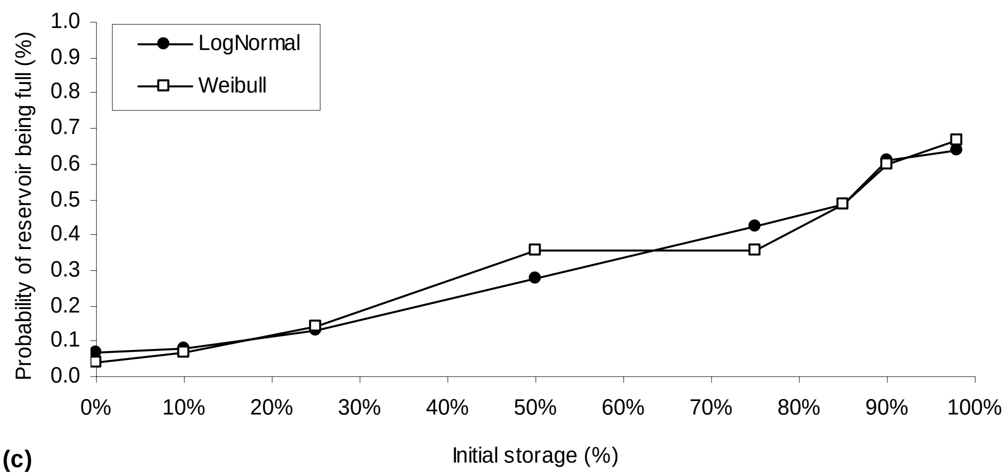

(c)

FIGURE B.1 Comparison of storage reliabilities using Weibull and lognormal distributions, using combination H, for (a) 1 month, (b) 3 months, (c) 6 months

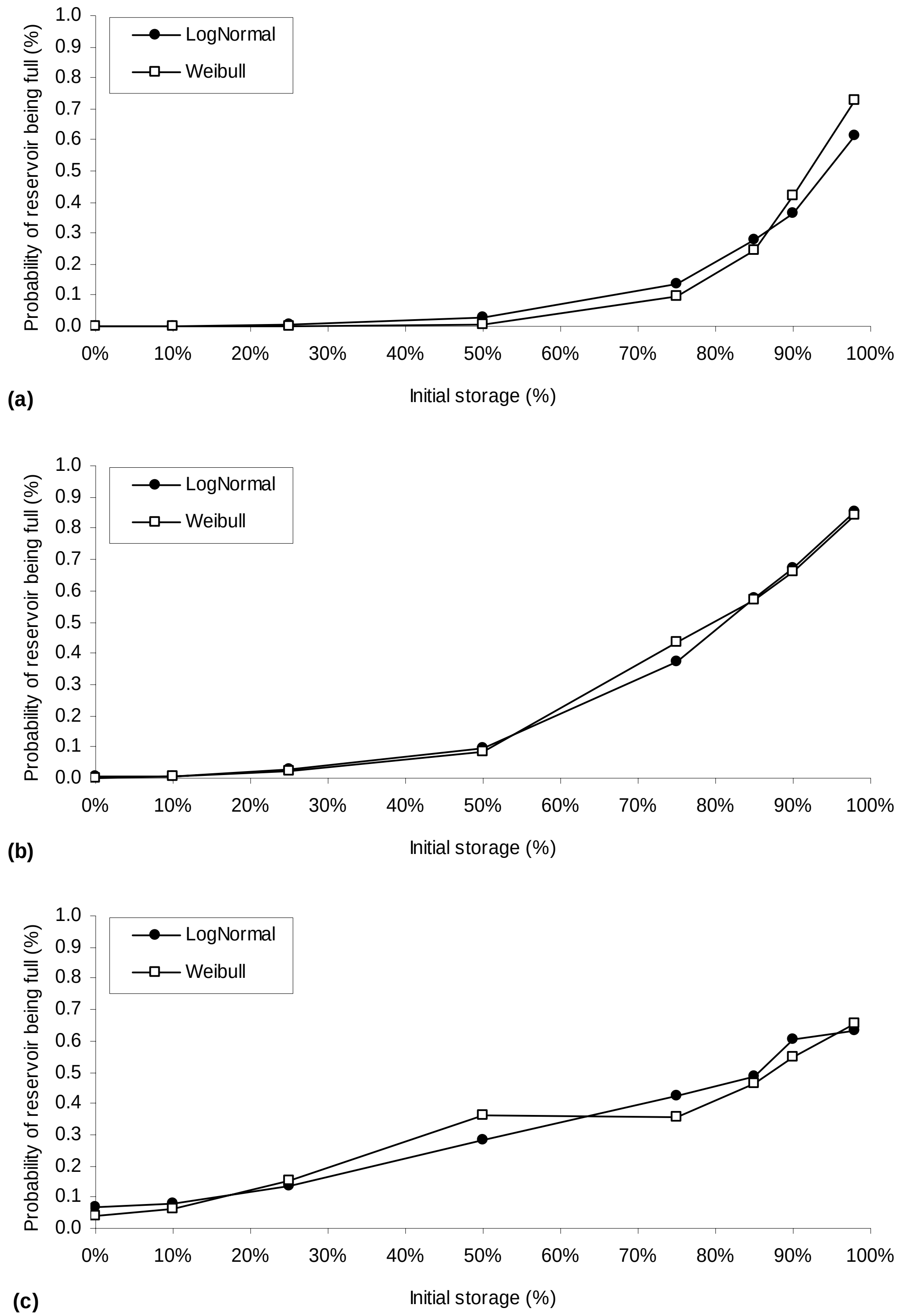

FIGURE B.2 Comparison of storage reliabilities using Weibull and lognormal distributions, using combination E, for (a) 1 month, (b) 3 months, (c) 6 months

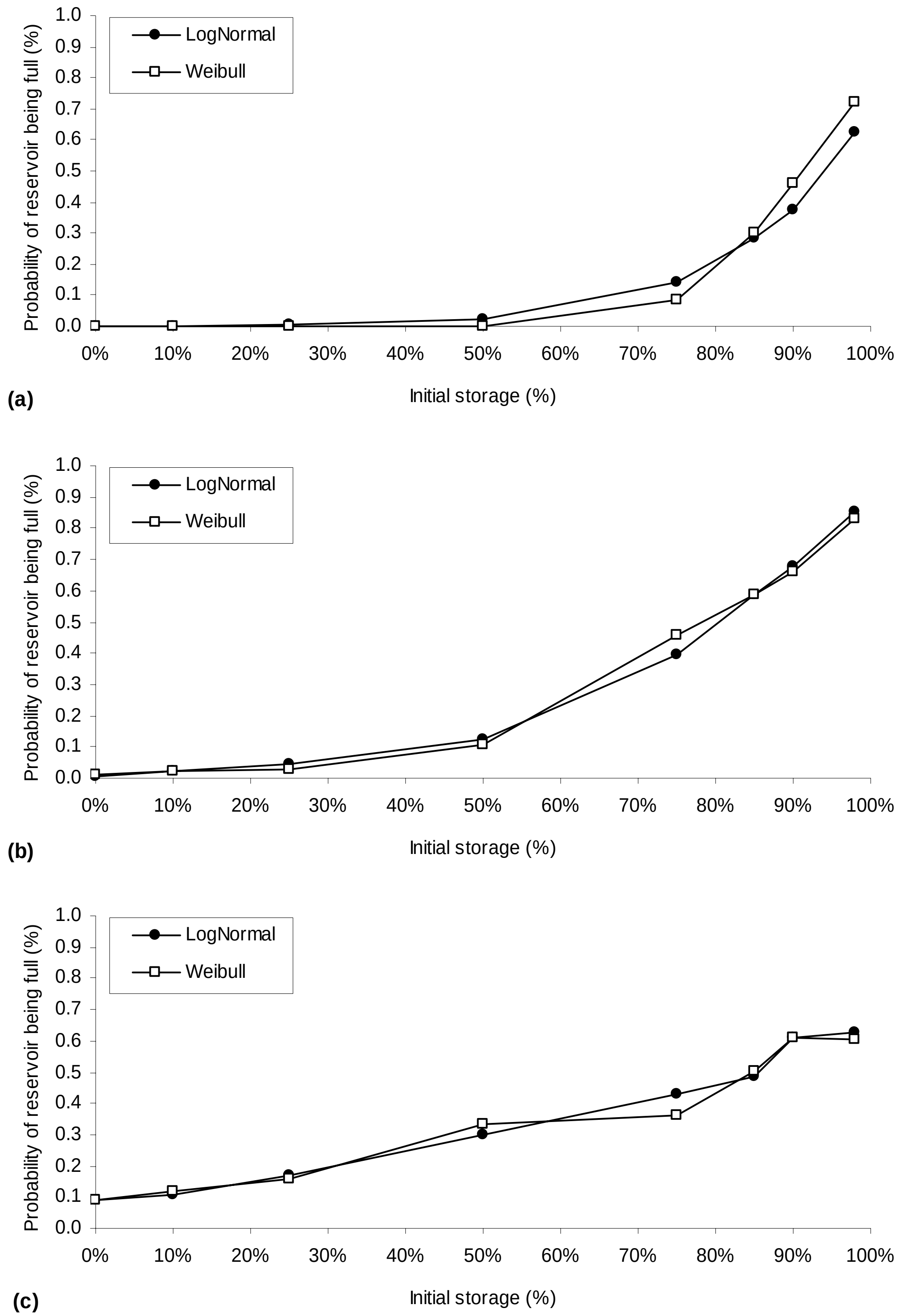

FIGURE B.3 Comparison of storage reliabilities using Weibull and lognormal distributions, using combination A, for (a) 1 month, (b) 3 months, (c) 6 months

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